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ABERDEEN UNIV (SCOTLAND) DEPT OF ENGINEERING
APPLICATION OF NUMERICAL METHODS TO THE CALCULATION OF ELECTROSTATICS ETC(U)
AUG 81 J R SMITH, P LEES, D MCALLISTER AFOSR-80-0223

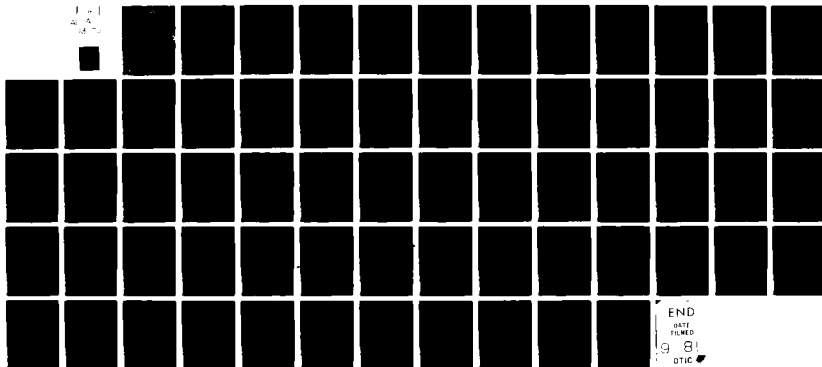
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APPLICATION OF NUMERICAL METHODS TO THE CALCULATION OF ELECTROSTATIC
FIELDS IN AIRCRAFT FUEL TANKS

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20. Abstract The solution of electrostatic field problems occurring during the refuelling of aircraft fuel tanks containing explosion suppressant foams is discussed. A computational model of a fuel tank is set up, and the finite element method is used to calculate the electrostatic potential distribution within the tank.		

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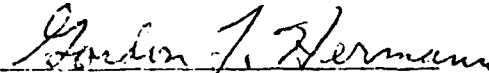
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1. ELECTROSTATIC HAZARDS IN AIRCRAFT FUEL TANKS DURING REFUELLING

The generation of high levels of electrostatic charge in hydrocarbon fuels (such as JP-4) during aircraft refuelling has long been recognized as an explosion hazard. The fuel is pumped at high flow rates through pipes, hoses, and filter/separators, and hence is exposed to relatively large liquid/solid interfaces. The double layer created at these interfaces coupled with the movement of fuel across them leads to a net unipolar charge being acquired by the fuel as it is swept along. The high charging tendency of a fuel such as JP-4, coupled with a low conductivity (typically < 10 pS/m) can lead to hazardous charge accumulation in the receiving tank. If resulting local electrostatic fields on the fuel surface exceed the breakdown value for the vapour space, electrostatic discharges may occur. Such a discharge may be incendive if (i) it has sufficient energy, and (ii) the fuel/air mixture lies in a flammable range (i.e. will support combustion). It is thus patently of importance to be able to estimate electrostatic potential and field distributions in fuel tanks for given charge distributions.

The introduction of polyurethane foam into fuel tanks to act as an explosion suppressant presents an additional problem. The foam itself acts as a secondary charge generating surface for the fuel (Ref. 1). The relaxation time of the charge in the tank increases enormously, thus leading to substantially increased levels of accumulated charge in the tank, since the charge is unable to relax to earth.

The present study is an attempt to apply numerical and computational techniques to the problem in order to examine the feasibility of providing useful working guides for estimating electrostatic potentials and fields in fuel tanks containing such foams.

2. THE MATHEMATICAL PROBLEM AND THE FINITE ELEMENT METHOD

One method of approach to the problem is to consider the fuel tank at various levels of filling, postulate a charge distribution and boundary conditions, and solve Poisson's equation for this situation. This approach has been tackled analytically for some very simple geometries and charge distributions (Refs. 2,3). For the modelling of realistic situations, however, the analysis becomes intractable, and recourse to numerical methods becomes essential.

Various numerical techniques for approximating the solution of electrostatic field problems are currently in use. These include the finite-difference method, the charge simulation method, the boundary integral method, and the finite element method. The method chosen for this study is the finite element method. It allows the modelling of complicated geometries, inhomogeneous charge distributions, and dielectric changes within the region of interest. Its disadvantages are relatively large data input and large computer storage requirements.

The basic mathematical problem to be tackled is the solution of Poisson's equation

$$\nabla^2 \phi = - \frac{\rho}{\epsilon_0 \epsilon_r}$$

within a region, subject to certain boundary conditions. Here, ϕ is the electrostatic potential, ρ is the space charge density, ϵ_0 is the

absolute permittivity (8.854×10^{-12} F/m) and ϵ_r is the relative dielectric constant of the medium. To provide a complete definition of problem, one or more of the following boundary conditions are required:

- (i) $\phi = f(s)$ which fixes the potential at the boundary s , as a specified function $f(s)$ of position.
(e.g. on an earthed boundary $\phi = 0$)
- (ii) $\frac{\partial \phi}{\partial n} = 0$ which forces equipotentials to cross a boundary normally
- (iii) $\frac{\partial \phi}{\partial n} = h(s)$ which superimposes a surface charge density distribution on a boundary.

Let us now consider the functional

$$F = \int_V \frac{1}{2} \{ |\nabla \phi|^2 - \frac{\rho}{\epsilon_0 \epsilon_r} \phi \} dV + \int_S h \phi dS$$

where V is the volume of the region of interest contained by the bounding surface S . If we minimise this functional, i.e. look for admissible potential functions ϕ such that

$$\delta F = 0$$

it may be shown that the ensuing Euler-Lagrange equation is

$$\nabla^2 \phi = - \frac{\rho}{\epsilon_0 \epsilon_r}$$

i.e. the potential function must satisfy Poisson's equation, subject to appropriate boundary conditions.

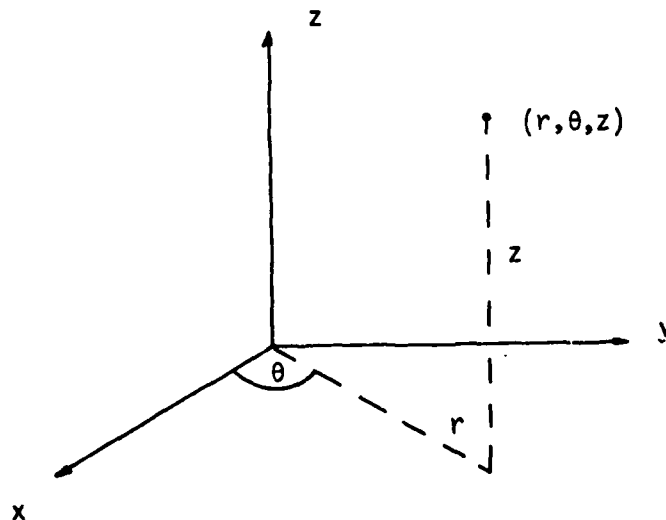
Briefly, the finite element method utilizes the above results by subdivision of the region of interest into a collection of elements, and approximating the potential by a set of piecewise continuous functions on these. Each element has a fixed number of nodes, and the

minimisation is performed in each element with respect to the potential values at these nodes.

For a full three-dimensional problem, however, the resulting set of linear equations in the nodal potentials to be solved is generally very large, and necessitates substantial computing resources. For many problems, however, including the one under consideration, the problem size may be reduced in size and complexity by using special features of the geometry. It will be seen that for the fuel tank under consideration, the geometry may be taken to be axisymmetric, yielding results which are sufficiently accurate to make the approximation acceptable. To exploit axisymmetry, cylindrical coordinates are adopted, and Poisson's equation becomes, in a usual notation,

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \phi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \phi}{\partial \theta^2} + \frac{\partial^2 \phi}{\partial z^2} = - \frac{\rho}{\epsilon_0 \epsilon_r} \quad (1)$$

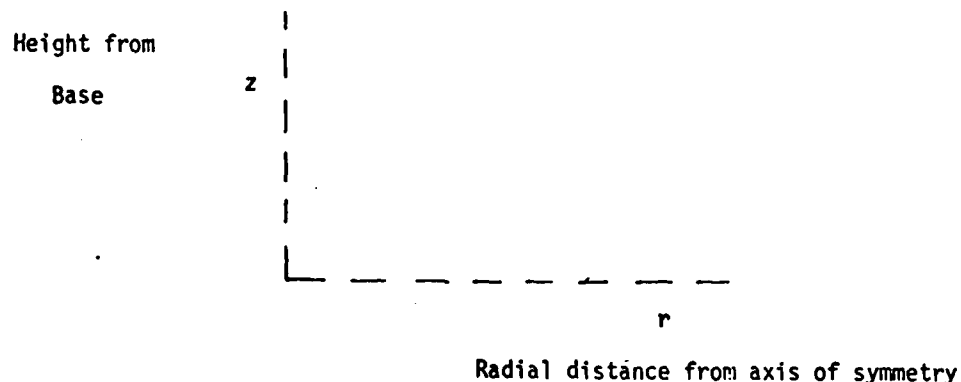
where r, θ, z are cylindrical coordinates as shown:



For axisymmetric problems, the geometry and charge distributions are rotationally symmetric, the potential ϕ , hence rotationally symmetric, and therefore independent of θ . Poisson's equation thus reduces to

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \phi}{\partial r} \right) + \frac{\partial^2 \phi}{\partial z^2} = - \frac{\rho}{\epsilon_0 \epsilon_r} \quad (2)$$

The problem is thus basically two-dimensional:



The finite element method consists of four basic steps. Firstly a grid of numbered nodal points is established over the region of interest, including the boundary. At each interior node the value of potential is to be determined. On the boundary ϕ or $\frac{\partial \phi}{\partial n}$, its normal derivative, is given. Secondly the nodes are interconnected to form a finite number of subregions which collectively approximate the region of interest.

Thirdly the potential is approximated by a continuous function over each subregion, continuity conditions being imposed at subregion boundaries. Finally the unknown values of the potential at the node points are calculated by means of a variational principle, e.g. minimisation of electrostatic energy.

The subregions used in this case are triangular. A first order interpolating polynomial (3) is used to approximate the potential distribution over each triangle.

$$\phi = \alpha_1 + \alpha_2 r + \alpha_3 z \quad (3)$$

Thus in a triangle whose nodes are labelled i, j, k we have -

$$\phi_i = \alpha_1 + \alpha_2 r_i + \alpha_3 z_i$$

$$\phi_j = \alpha_1 + \alpha_2 r_j + \alpha_3 z_j$$

$$\phi_k = \alpha_1 + \alpha_2 r_k + \alpha_3 z_k$$

The variables $\alpha_1, \alpha_2, \alpha_3$ can therefore be obtained in terms of ϕ_i, ϕ_j, ϕ_k and the coordinates of the nodes i, j, k. Substituting back into the interpolating polynomial (3) gives -

$$\phi = N_i \phi_i + N_j \phi_j + N_k \phi_k \quad (4)$$

where N_i, N_j, N_k are functions of $r_i, r_j, r_k, z_i, z_j, z_k, r$ and z .

$\frac{\partial \phi}{\partial r}$ and $\frac{\partial \phi}{\partial z}$ may also be readily obtained.

The unknown values of ϕ may now be obtained by minimising the functional -

$$F = \int_A \left\{ r \left(\frac{\partial \phi}{\partial r} \right)^2 + r \left(\frac{\partial \phi}{\partial z} \right)^2 - \frac{2 \rho r \phi}{\epsilon_0 \epsilon_r} \right\} dA - 2 \int_C \phi h(s) ds$$

i.e. $\delta F = 0$

It is not difficult to show that this minimisation is equivalent to the requirement that ϕ satisfies the axisymmetric Poisson equation with appropriate boundary conditions.

Substitution of the appropriate local expressions for $\phi, \frac{\partial \phi}{\partial r}$ and $\frac{\partial \phi}{\partial z}$ into the functional, and minimisation by a Rayleigh-Ritz or equivalent technique yields a set of simultaneous equations in the nodal potentials for each triangle. These elemental equations are then assembled to give a global set of equations which may be solved using standard techniques.

3. DESCRIPTION OF COMPUTATIONAL MODEL

(i) Geometry

The computational model used is based on the drawings of an A-10 fuel tank (Ref. 4). The real tank configuration (Figure 1) is such as to permit an axisymmetric approximation. The axisymmetric configuration chosen is shown in Figure (2), cut away to show the inlet nozzle and the explosion suppressant foam blocks. A dimensional cross-section of the tank is shown in Figure (3). (Dimensions are in millimetres).

(ii) Boundary Conditions

Figure (4) illustrates the assumed boundary conditions. The tank walls and the inlet nozzle are assumed to be at earth potential ($\phi = 0$).

Conforming to the real situation, the foam is divided into two categories, fixed and removable. Section 4 in Figure (4) corresponds to the fixed foam region. Sections 1, 2, and 3 correspond to removable foam target sections. Thus, possible target configurations are Section 1 only, Sections 1 and 2 together, or Sections 1, 2, and 3 together, allowing alteration of the voiding volume.

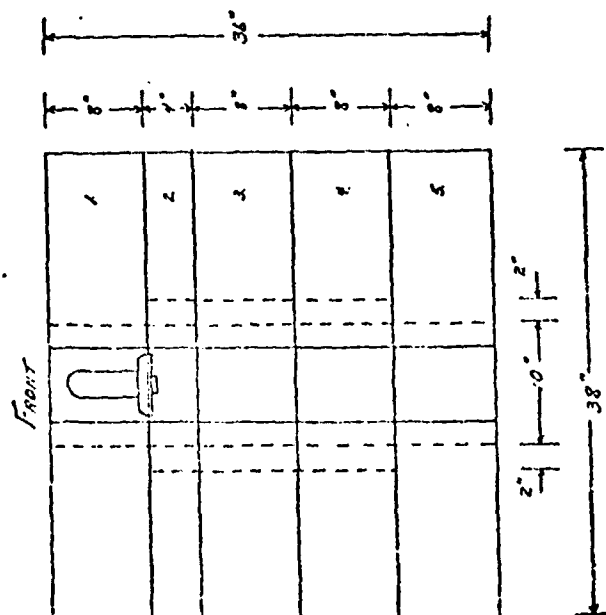
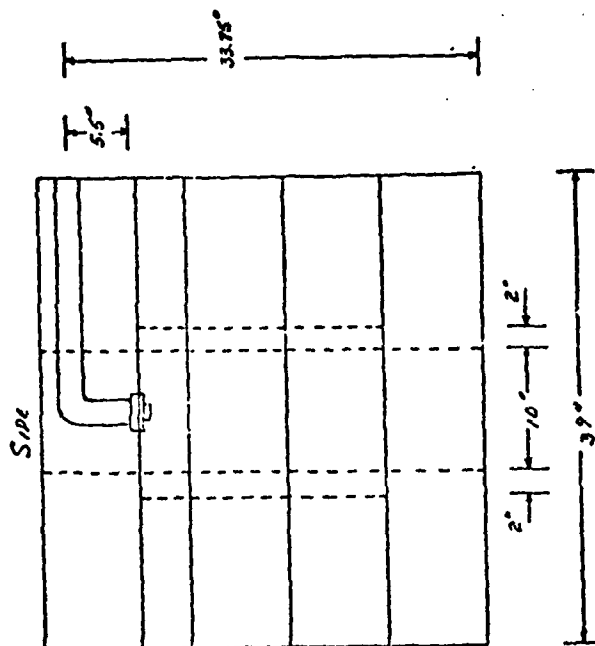
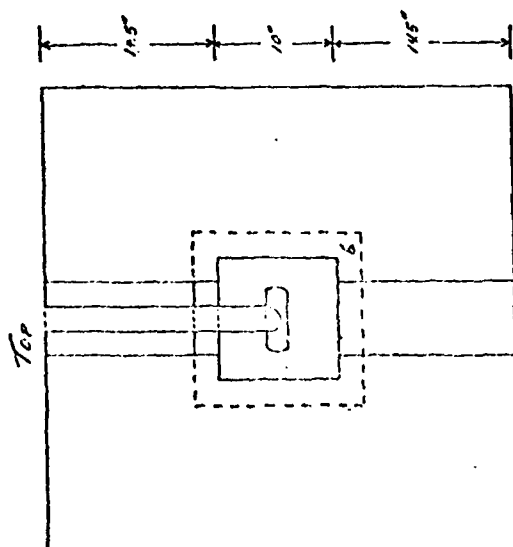
The dielectric boundaries of the foam blocks are also shown in Figure (4), as is the axis of symmetry. Since the problem is axisymmetric, the potential ϕ must satisfy $\frac{\partial \phi}{\partial n} = 0$ on the axis of symmetry, i.e. the equipotentials must cross the axis normally.

(iii) The Charge Density

Accurate estimations of the volume and surface charge densities occurring when fuel is pumped at speed into a receiving tank are difficult

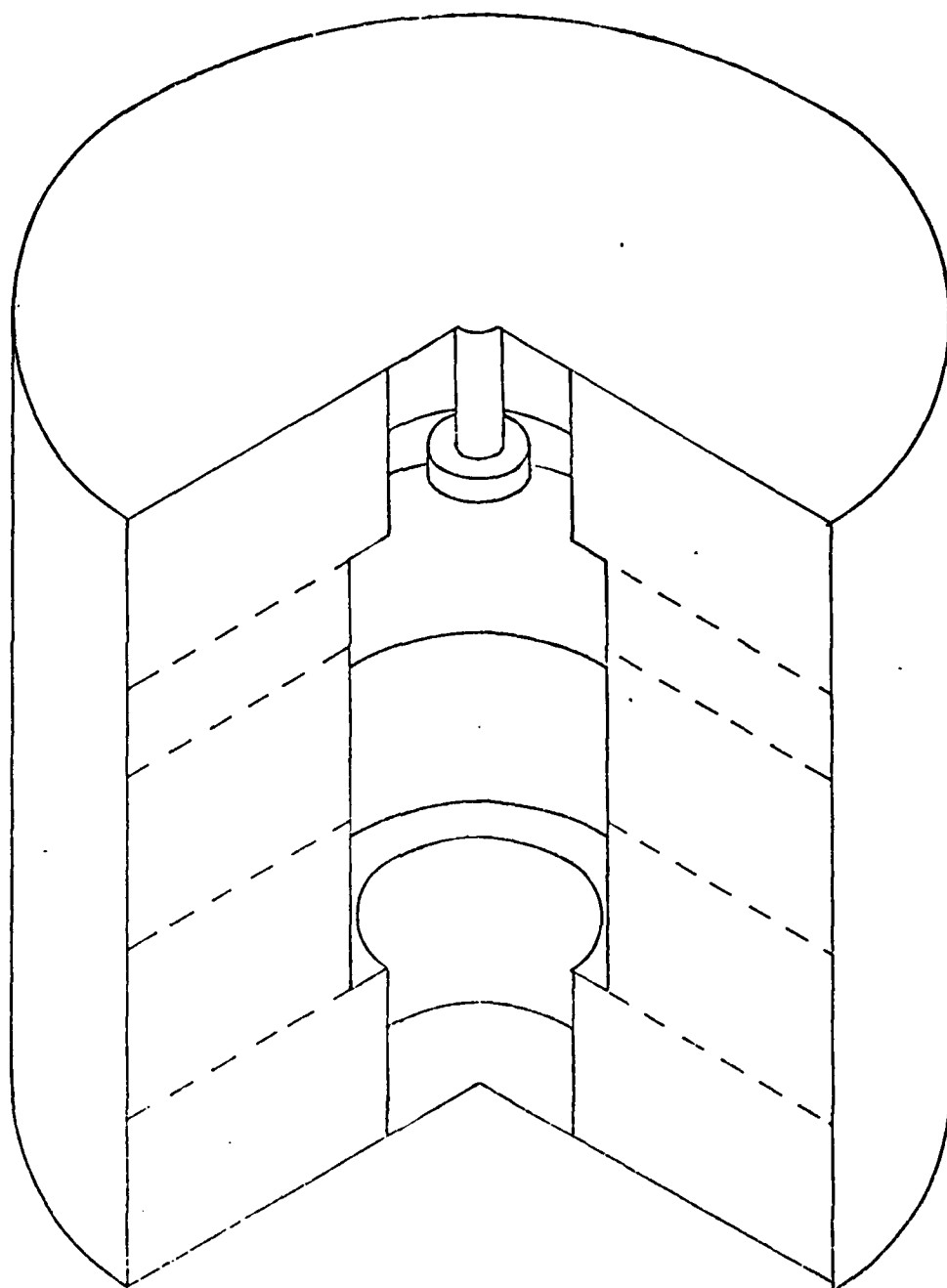
VOIDING CONCEPT ILLUSTRATES FUTURE POLYETHER
BLUE CROSS PORO FORM CRITERIA
FOR THE F-4 AIRCRAFT

1. TOP PIECE OF FOAM WITH A 10"x10"x8" VOID AND A 6"x8"x14.6" REMOVABLE
2. TOP MIDDLE PIECE OF FOAM WITH A 14"x14"x4" VOID AND A 6"x4"x12.8" REMOVABLE
3. MIDDLE PIECE OF FOAM WITH A 14"x14"x8" VOID AND A 6"x8"x12.5" REMOVABLE
4. BOTTOM MIDDLE PIECE OF FOAM WITH A 14"x14"x8" VOID AND A 6"x8"x12.5" REMOVABLE
5. BOTTOM PIECE OF FOAM WITH A 10"x10"x8" VOID AND A 6"x8"x14.6" REMOVABLE
6. THREET FORM SECTION 14"x14"x20" WITH A 10"x10"x20" VOID.



A-10 Fuel Tank

Fig. 1.



Isometric Projection of Tank Model

fig. 2.

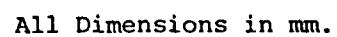
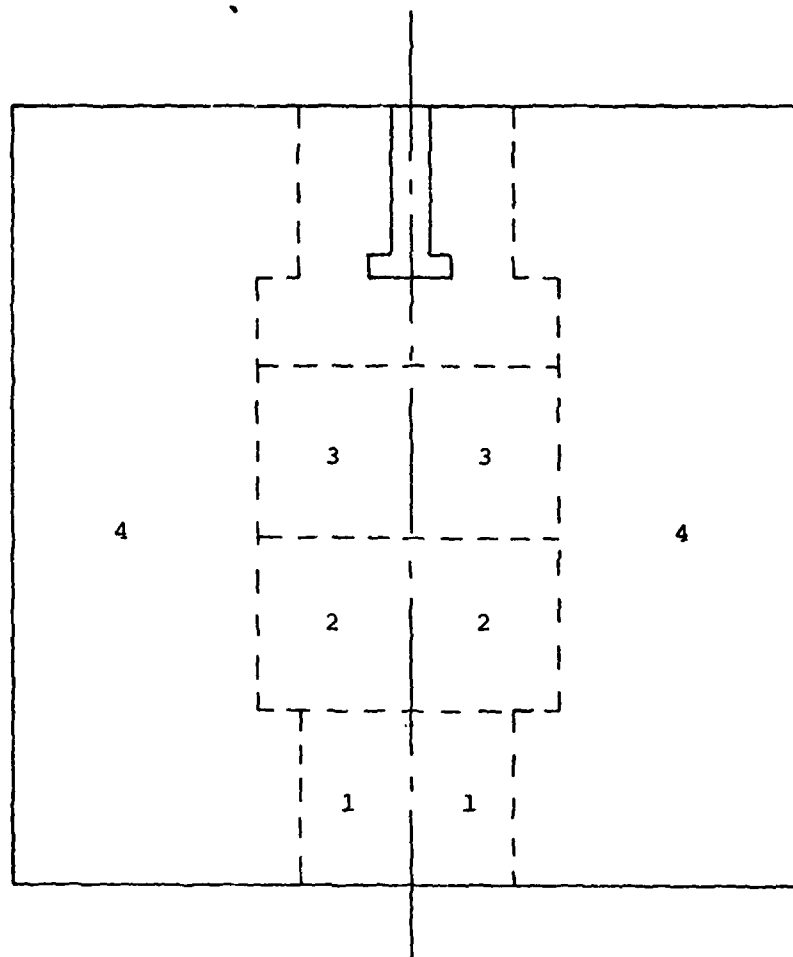


fig. 3.



- Earthed boundaries
- - - - Dielectric boundaries
- . - . Axis of symmetry
- 1 Target section 1
- 2 Target section 2
- 3 Target section 3
- 4 Fixed foam region

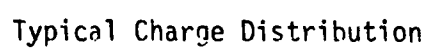
Section of Tank Model showing Target Sections

fig. 4.

to obtain. Factors such as fuel conductivity, rate of flow, turbulence, all contribute to the distribution of charge in the fuel at any particular time. The simplest, and not unrealistic, distribution to assume is a constant charge density within the fuel. There is evidence (Ref. 5) that jet fuels such as JP-4 generate static electricity when passing through porous media. The explosion suppressant foam acts as a secondary static charge generating surface. Furthermore, the movement of charge with foam present is very slow, so a constant charge density at any filling level is a reasonable approximation. The dielectric constant of both fuel and foam has been taken to be 2. A typical charge distribution considered is shown in Figure (5). As we shall see, the charge distributions studied at various filling levels allow a wide choice of postulated charge distribution.

4. RESULTS

The cases studied consist of charge distributions, both volume and surface, for various filling levels, and for different target sections. A 'standard' constant volume charge distribution of 10^{-4} C/m^3 in the fuel was chosen, together with a 'standard' surface charge distribution of 10^{-3} C/m^2 on the foam surface in the voiding region. This is not restricted since the two charge distributions are treated separately, and the principle of superposition allows simple scaling to a desired charge density. The plots provided give ten equipotentials between minimum and maximum potentials for each situation. Also given are plots of electrostatic field along the axis of symmetry for each configuration.



Page 13

PLOTS 1 - 17

The configuration for plots 1-17 consists of foam Section 4 together with foam Section 1 inserted. (See Figure 6).

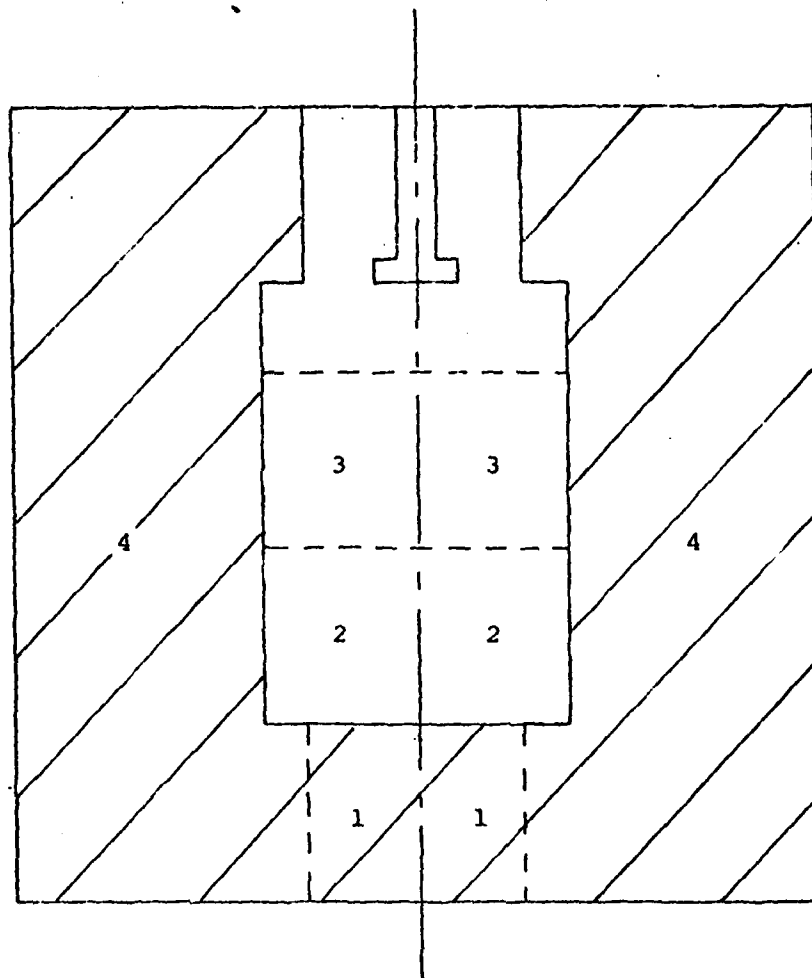
Plots 1 - 5 Charge density in fuel $\approx 10^{-4} \text{ C/m}^3$
 Charge density on foam surface $\approx 0 \text{ C/m}^2$
 Filling levels at .1, .2, .3, .4, .5 metres above base.

Plot 6 Surface charge density of 10^{-3} C/m^2 on Section 1
 upper surface only.

Plots 7 - 11 Surface charge on Section 1 upper surface and at
 heights .1, .2, .3, .4, .5 metres above this surface.

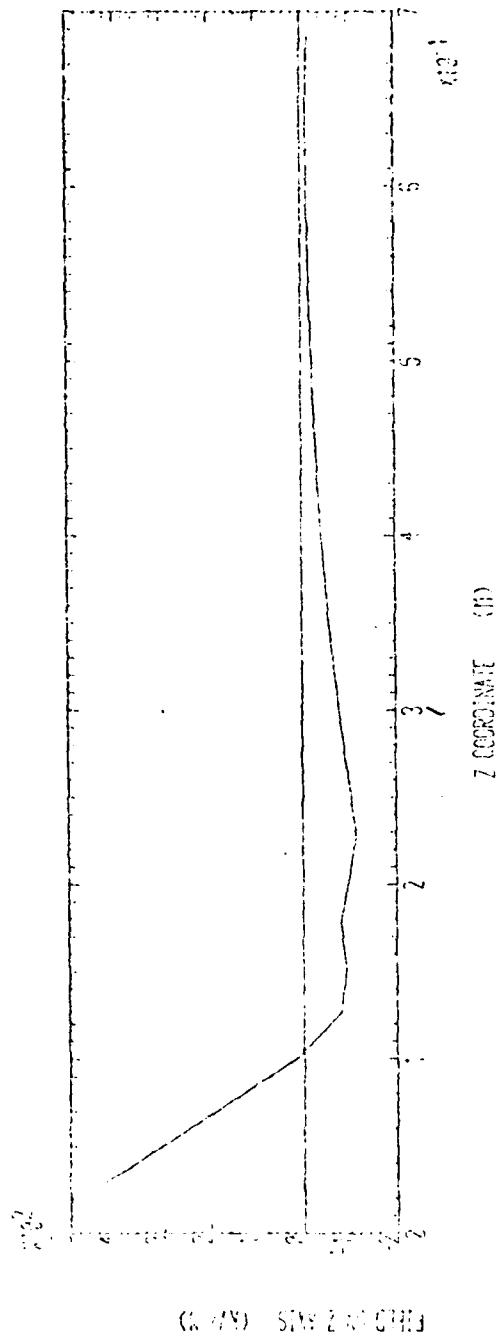
Plot 12 Vertical stream of fuel with charge density 10^{-4} C/m^3
 impinging on the target area.

Plots 13 - 17 Vertical stream of fuel + voiding region filled to
 heights .1, .2, .3, .4, .5 metres.

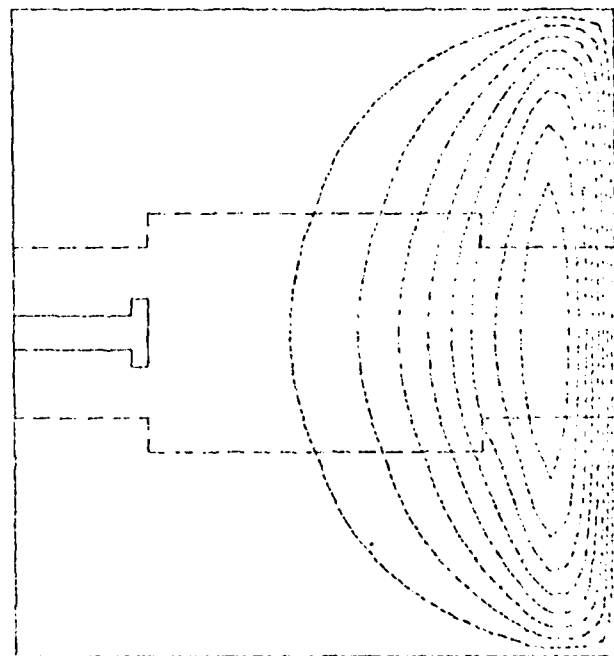


Foam sections 1 and 4 in place

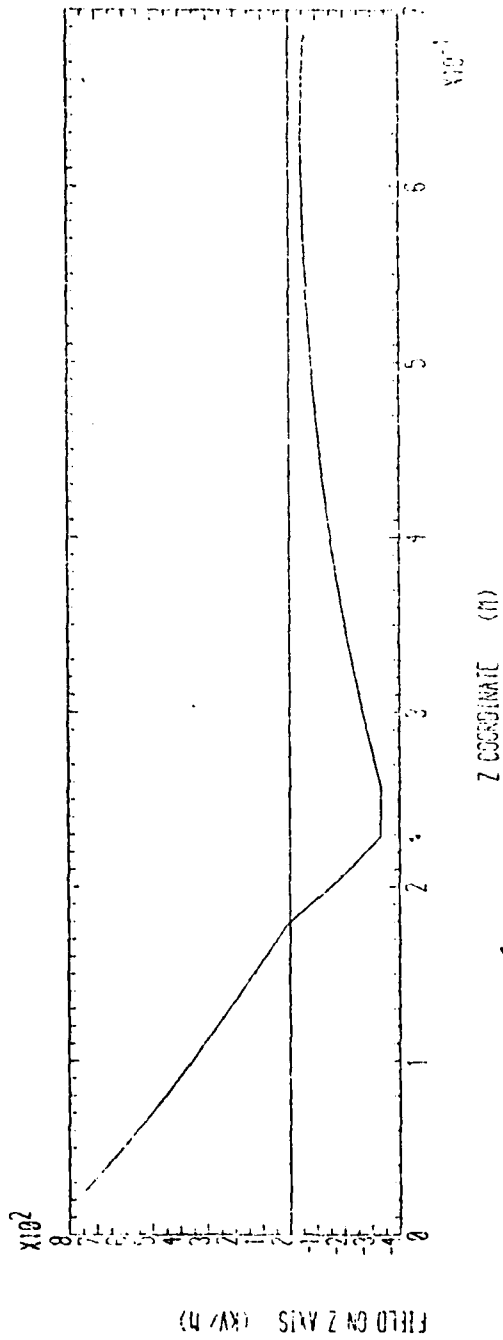
fig. 6.



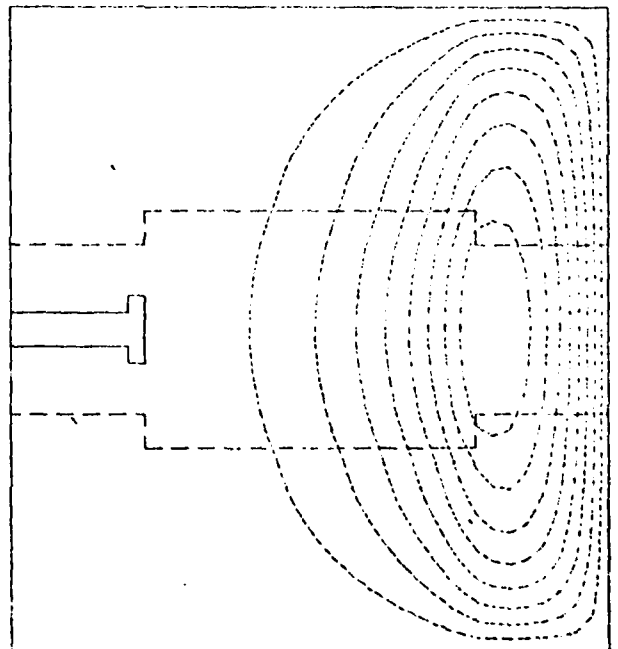
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MAXIMUM POTENTIAL	(KV) .0003E 5
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CHARGE DISTRIBUTION ON FOAM	(C/CM2) .0002E 0
FILLING LEVEL	(M) .1016E 0
CONTOUR SPACING	(KV) .3393E -4



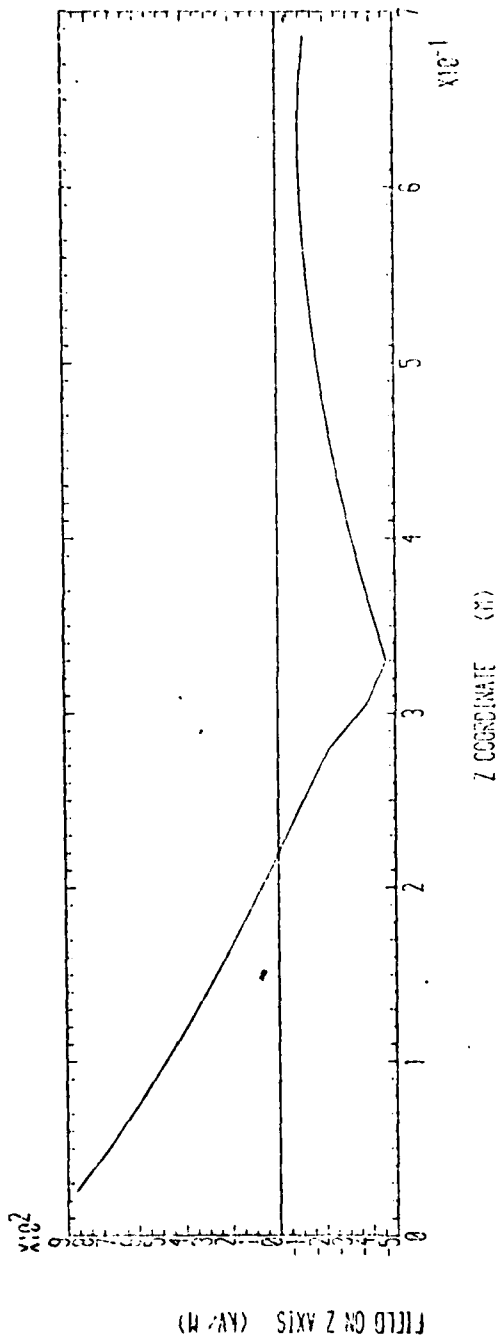
PILOT 1



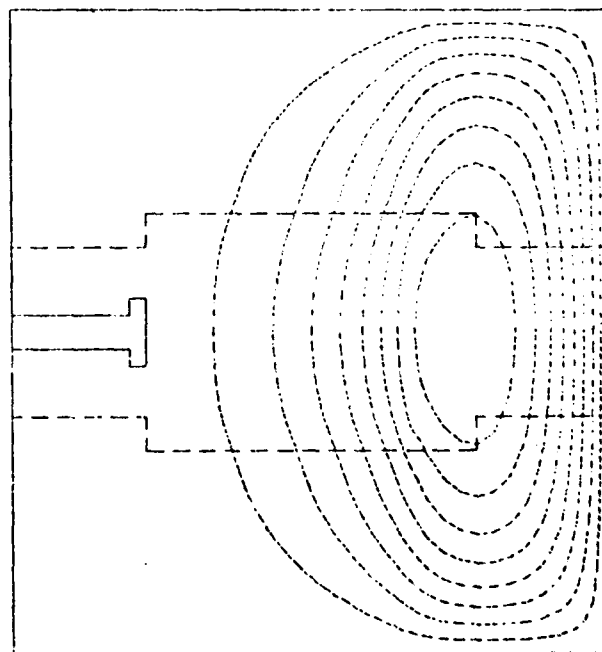
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MAXIMUM POTENTIAL	UAV 1.7000E-05
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CHARGE DISTRIBUTION ON FOAM	LC/M2 1.0000E-02
FILLING LEVEL	1.0000E-01
CONTAINER SPACING	UAV 1.0000E-04



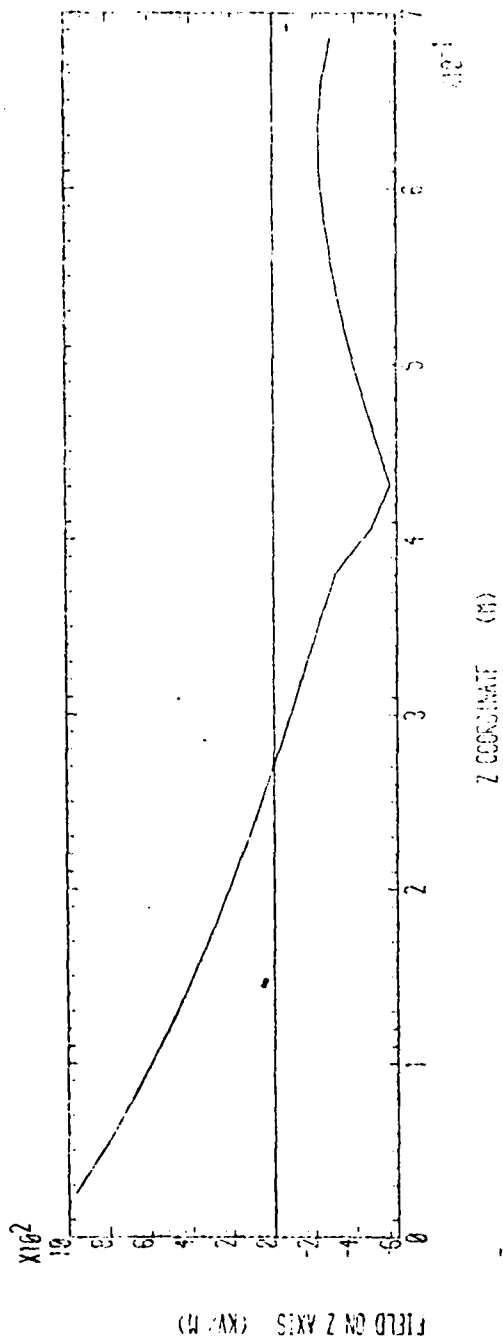
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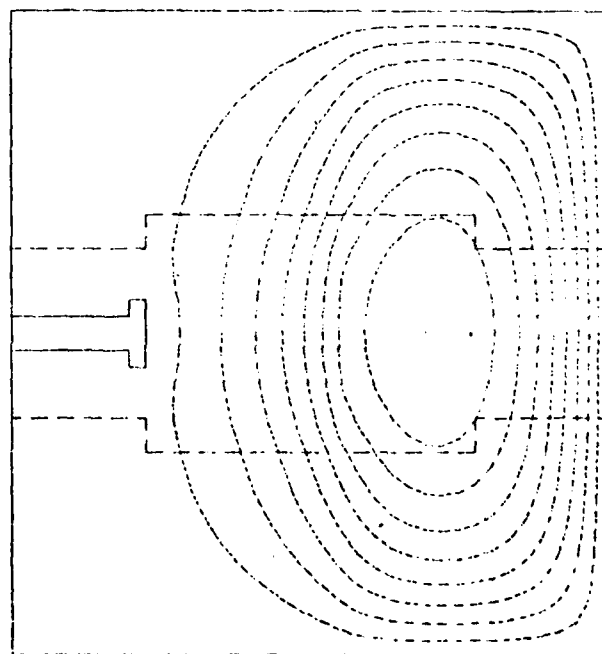
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MAXIMUM POTENTIAL	(AV) 1.0000E 0
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CHARGE DISTRIBUTION ON FOAM	1.0000E 0
FILLING LEVEL	0.0000E 0
CONTOUR SPACING	(AV) 1.111E 0



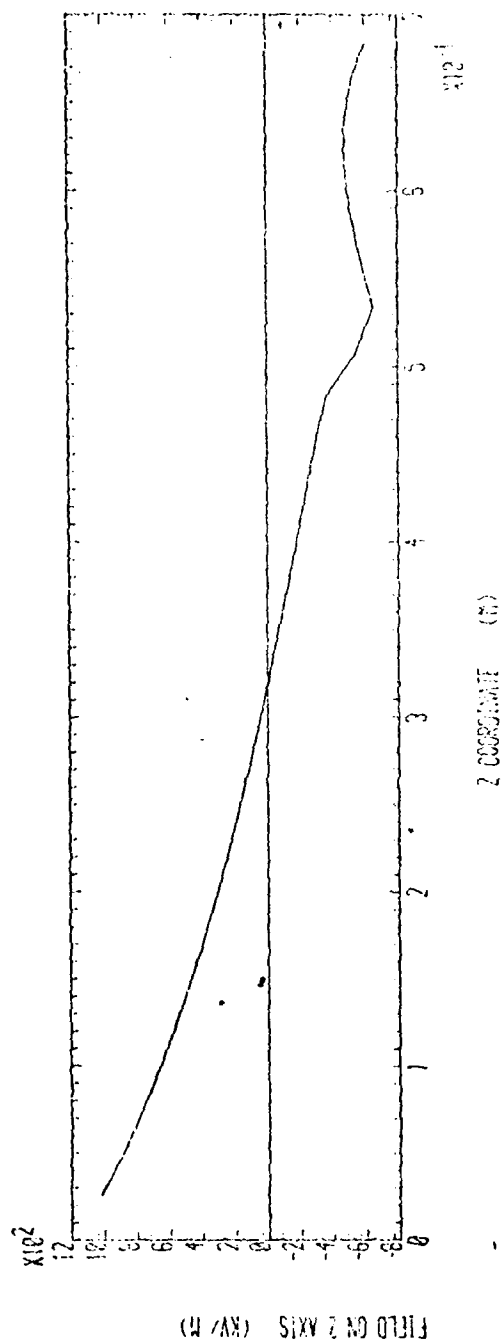
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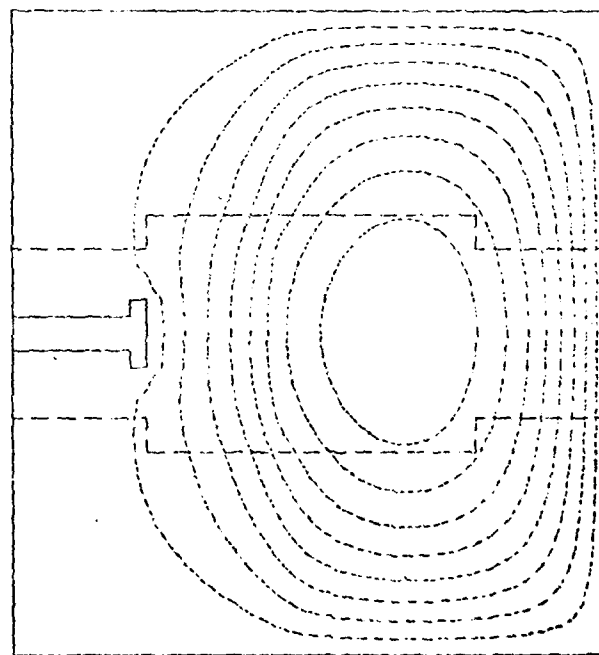
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MAXIMUM POTENTIAL	(KV) 1.000E - 8
CHARGE DENSITY IN FUEL	(C/M ³) 1.000E - 8
CHARGE DISTRIBUTION ON FOAM	(C/M ²) 1.000E - 8
FILLING LEVEL	(M) 1.000E - 2
CONTOUR SPACING	(KV) 1.000E - 8



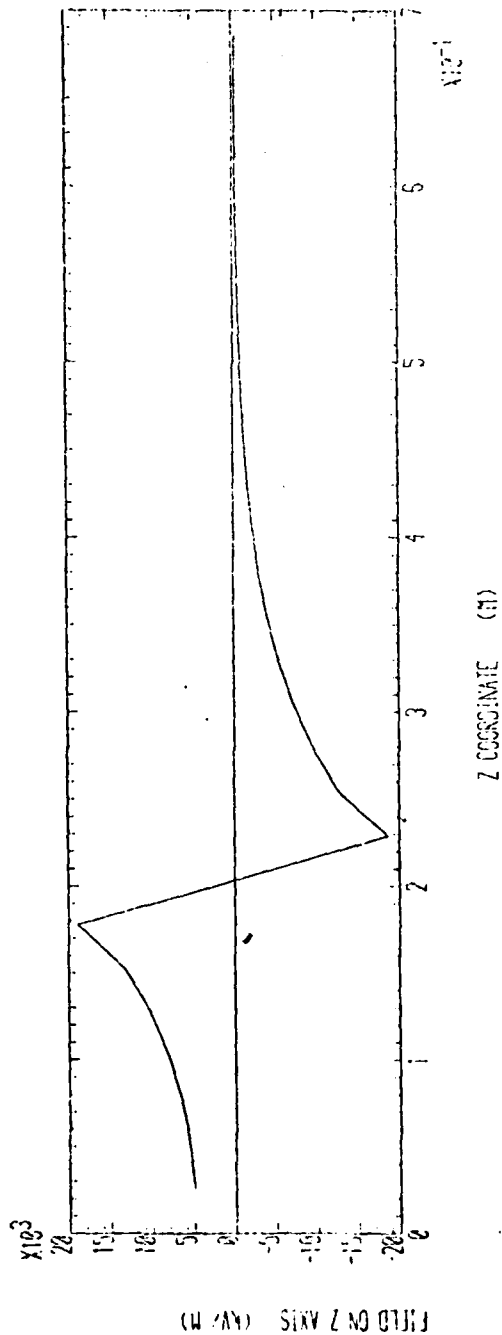
PLOT 4



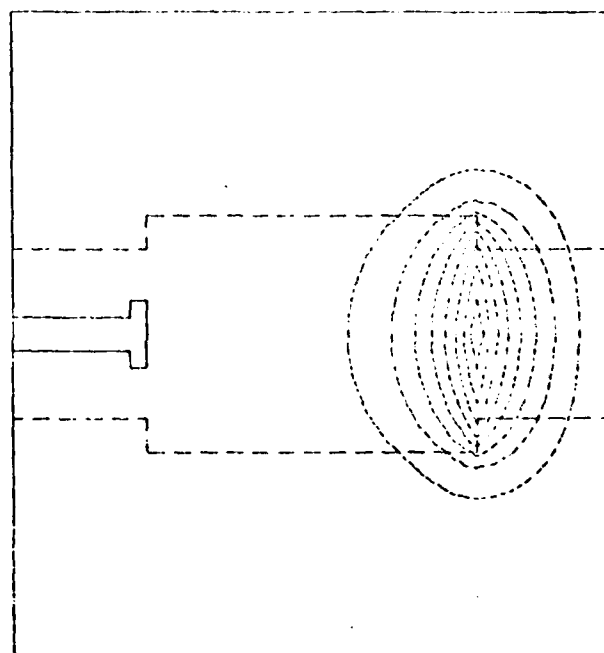
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MAXIMUM POTENTIAL	UNVJ .1500E 6
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CHARGE DISTRIBUTION ON FOAM	LCNMD .0000E 0
FILLING LEVEL
CONTOUR SPACING	LCVJ .1000E 5



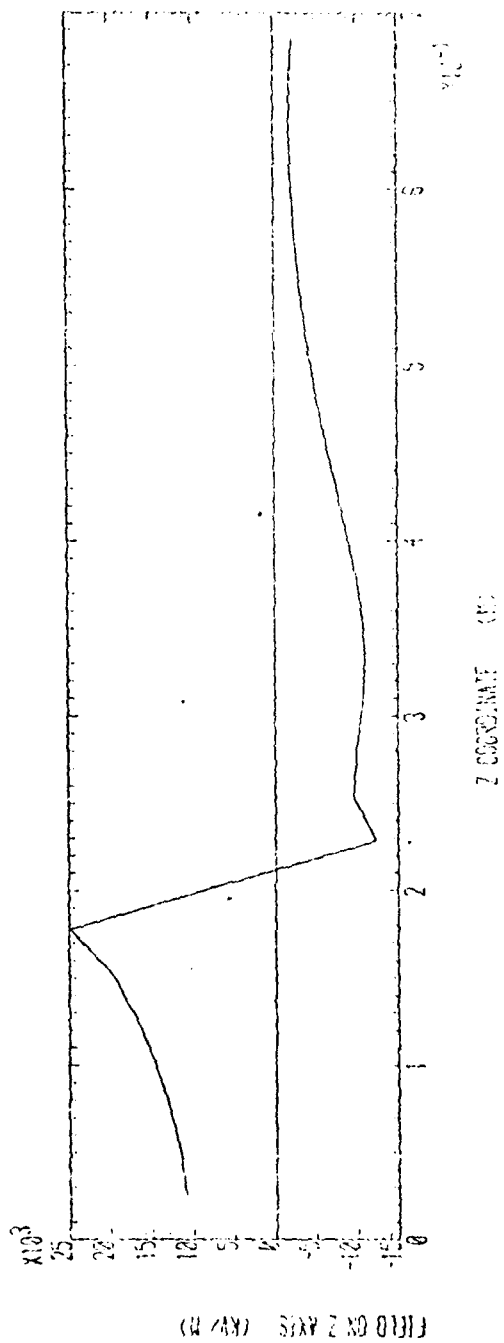
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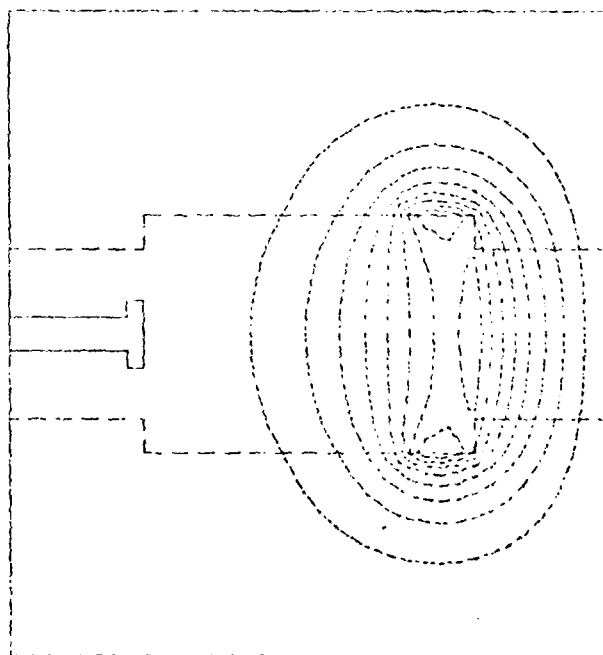
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CHARGE DISTRIBUTION ON FOAM	(CMF2) .0000E 0
FILLING LEVEL	(FNL) .0000E 0
CONTOUR SPACING	(CNV) .0000E 0



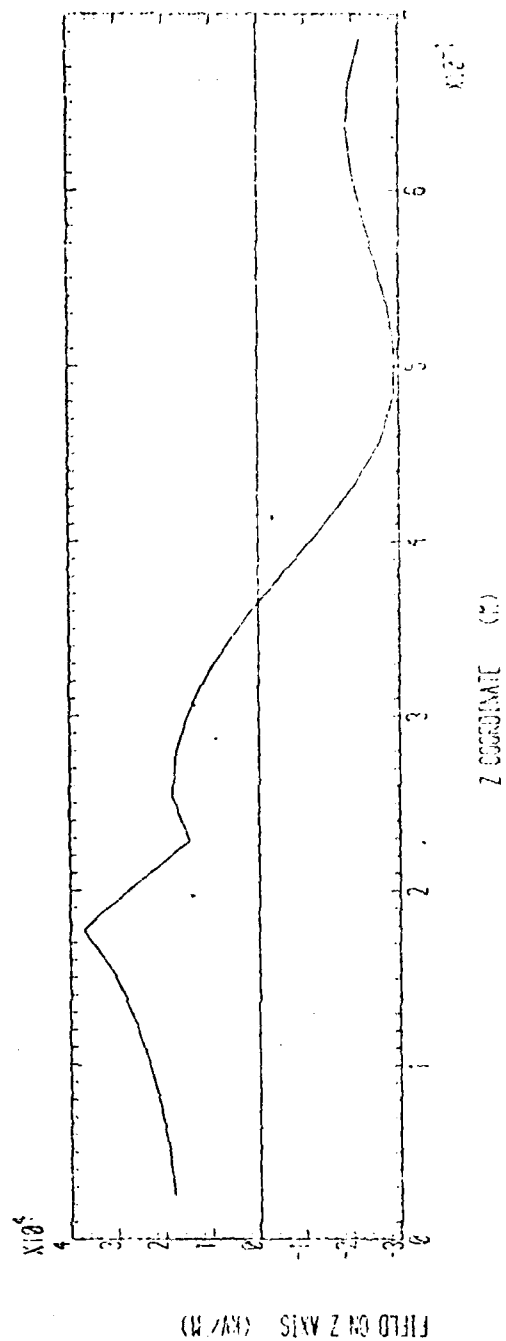
PLOT 6



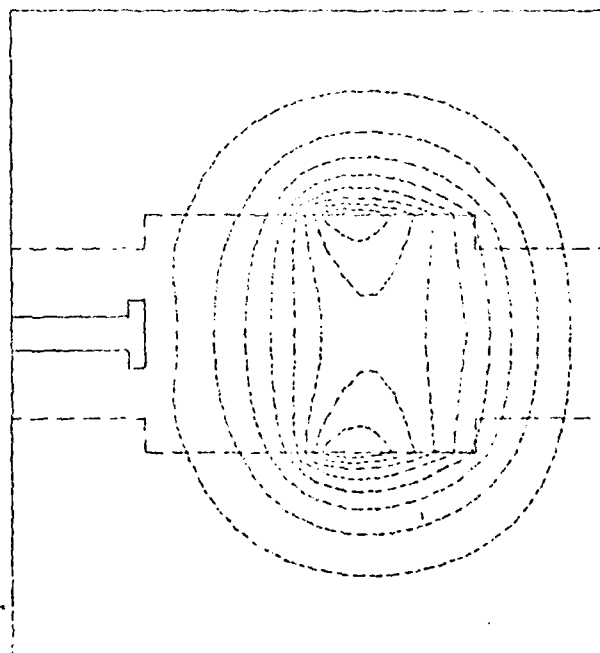
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CHARGE CONTRIBUTION ON FUEL	10/100 VOLTS
FILLING LEVEL	100 VOLTS
CONTOUR SPACING	100 VOLTS



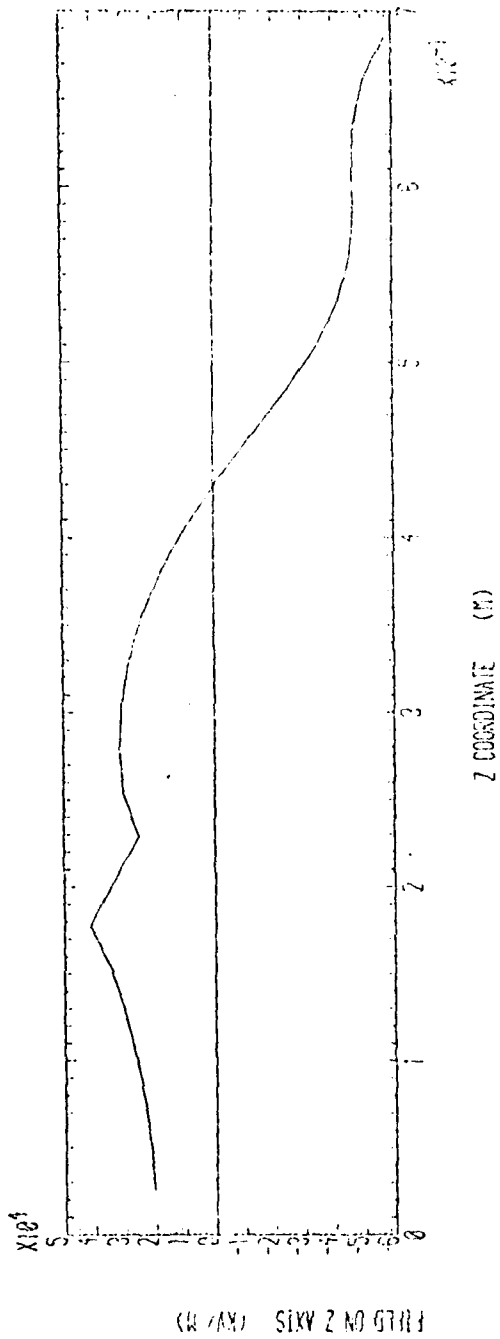
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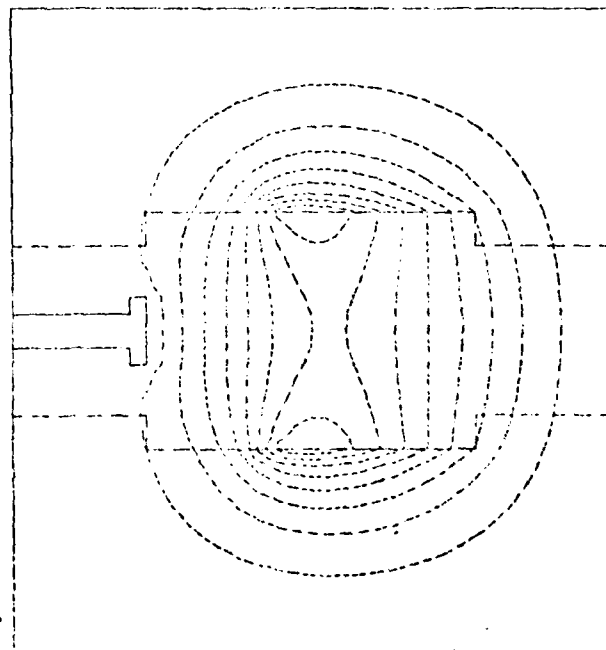
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CHARGE DISTRIBUTION ON FOAM	10V100 10000 2
FILLING LEVEL	10V1 10000 2
CONTAINER SPACING	10V1 10000 2



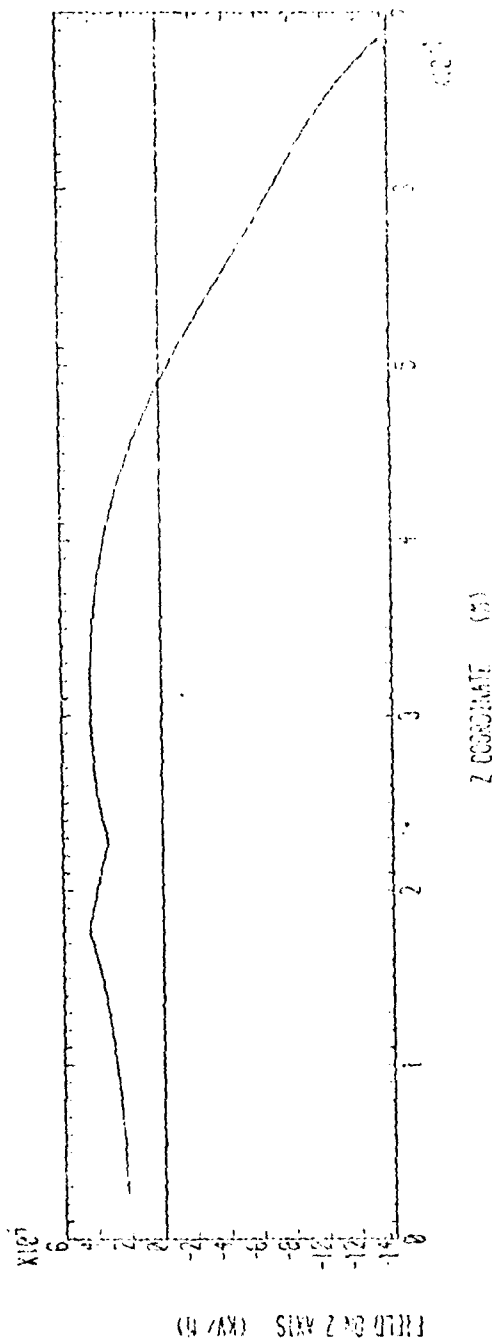
PLOT 9



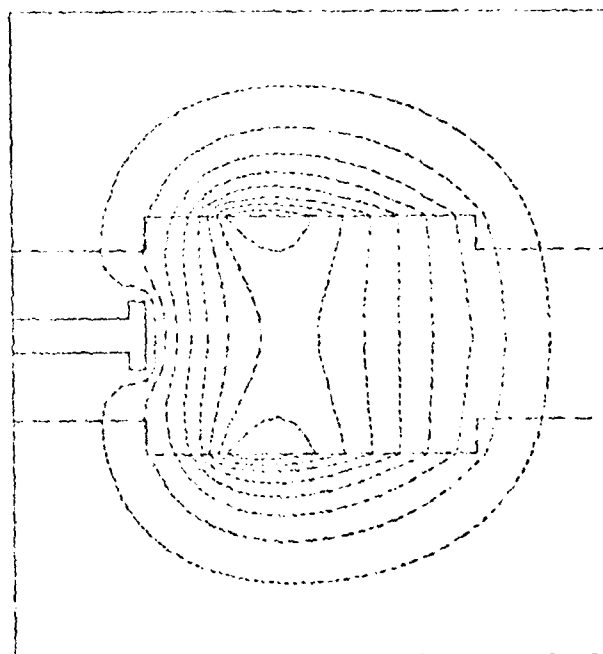
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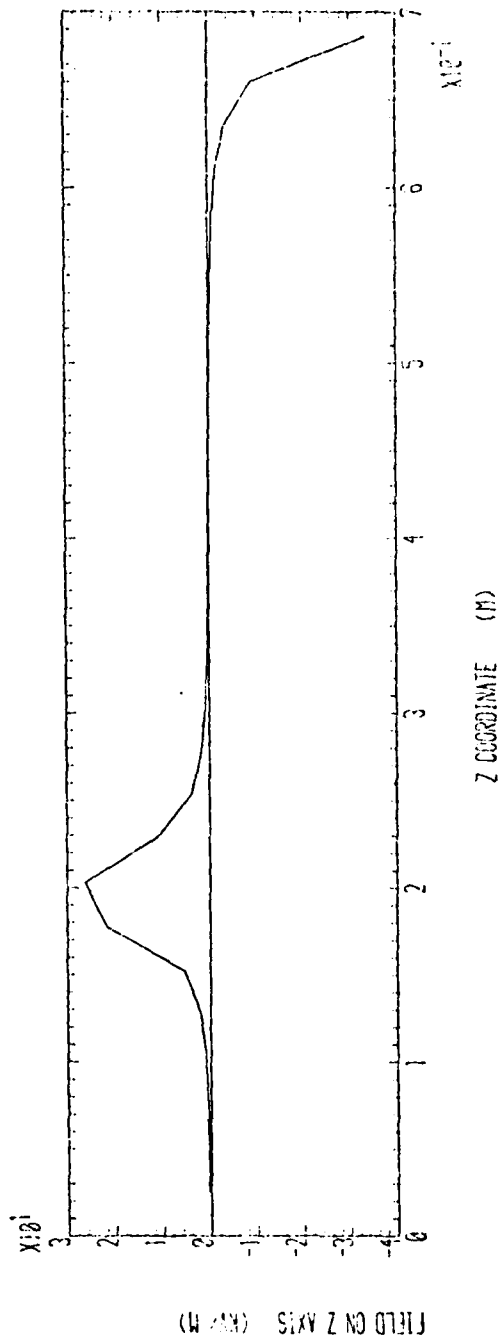
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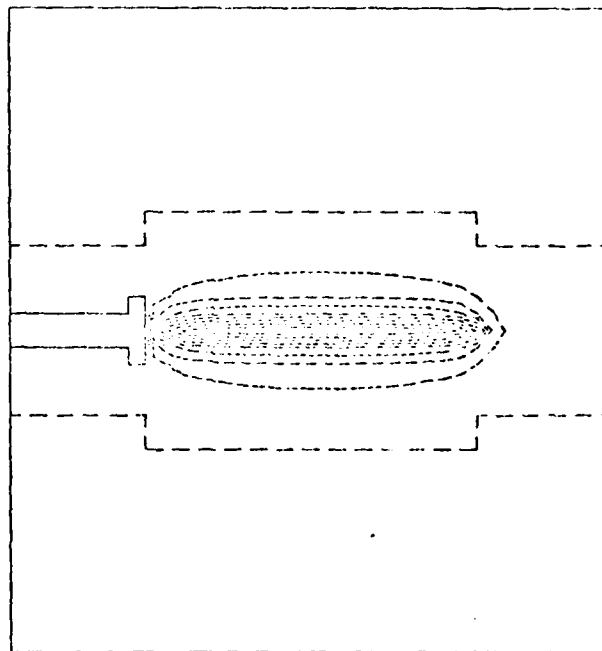
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 MAXIMUM POTENTIAL 1000 VOLTS
 CHARGE DENSITY IN FUEL 10000 VOLTS
 CHARGE DENSITY ON FLOW 10000 VOLTS
 FLOWING IN FUEL 10000 VOLTS
 CONTAIN DRAINING 10000 VOLTS



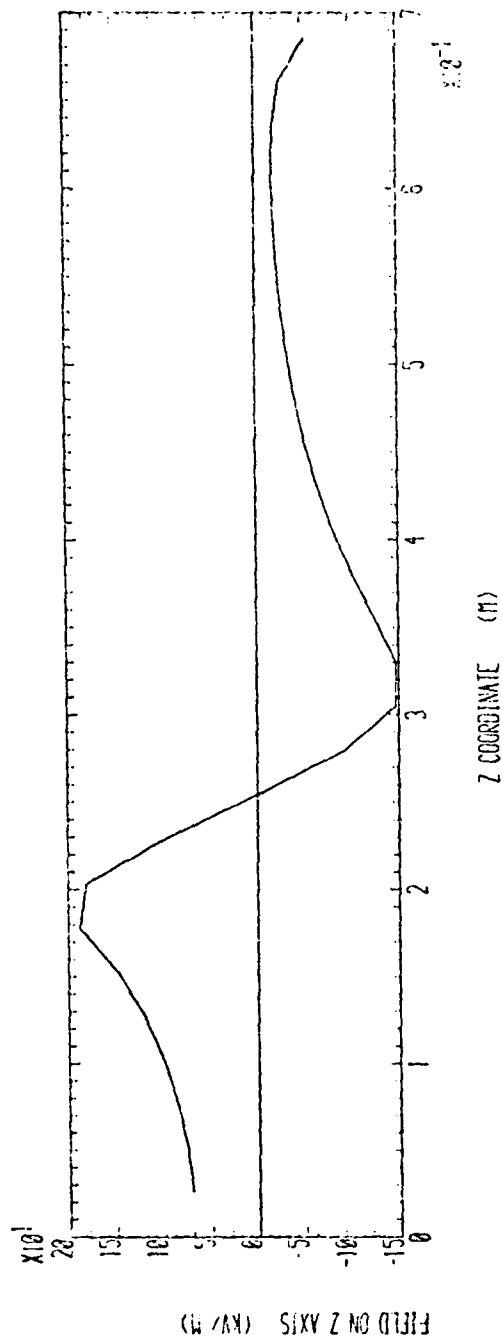
PLOT 11



MINIMUM POTENTIAL	(KV) .0000E 0
MAXIMUM POTENTIAL	(KV) .1500E 4
CHARGE DENSITY IN FUEL	(C/M ³) .1200E -3
CHARGE DISTRIBUTION ON FOAM	(C/M ²) .0000E 0
FILLING LEVEL	(M) .0000E 0
CONTOUR SPACING	(KV) .2165E 3

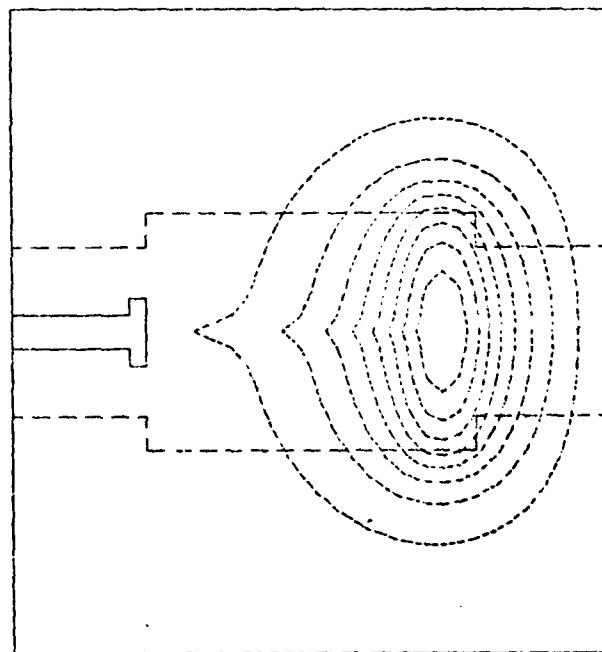


PLOT 12

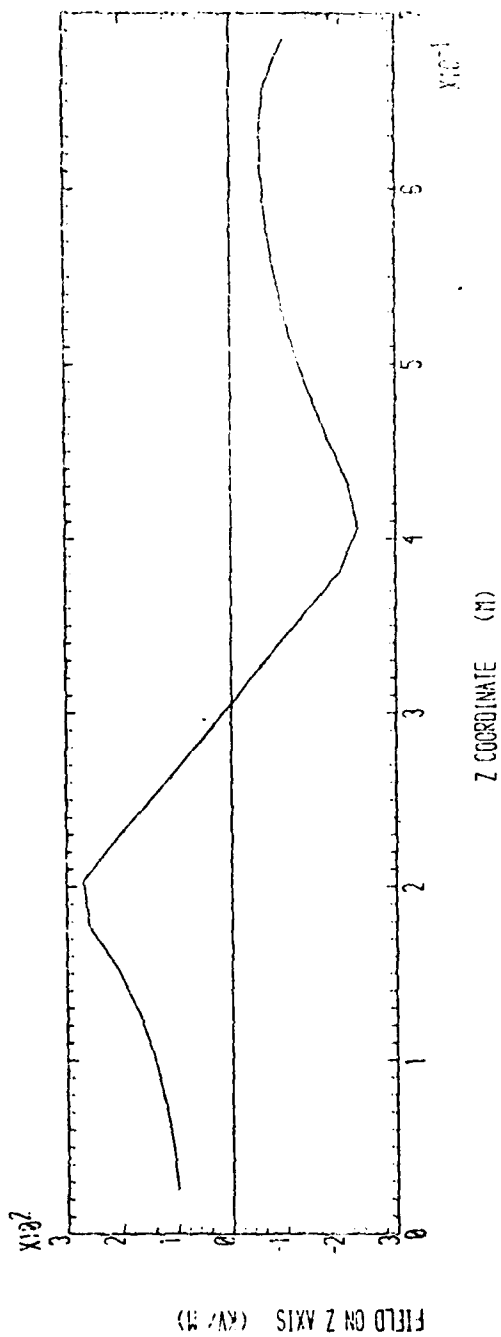


MINIMUM POTENTIAL
 MAXIMUM POTENTIAL
 CHARGE DENSITY IN FUEL
 CHARGE DISTRIBUTION ON FOAM
 FILLING LEVEL
 CONTOUR SPACING

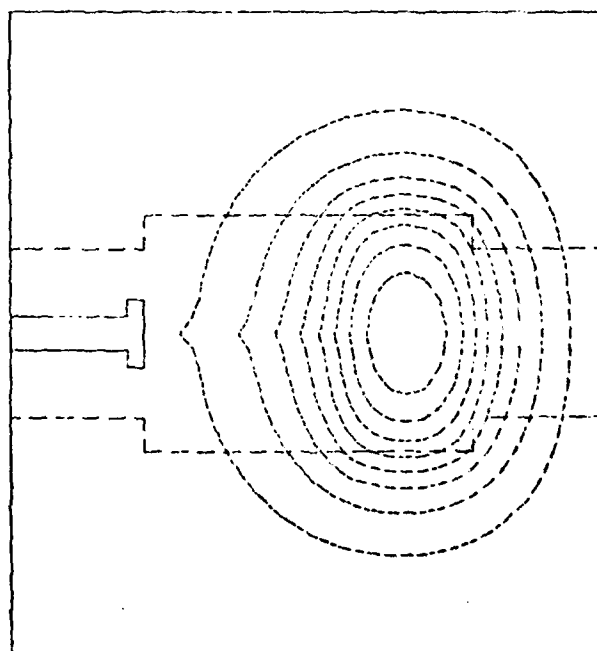
10/1000 0
 10/1000 0
 10/1000 0
 10/1000 0
 10/1000 0
 10/1000 0



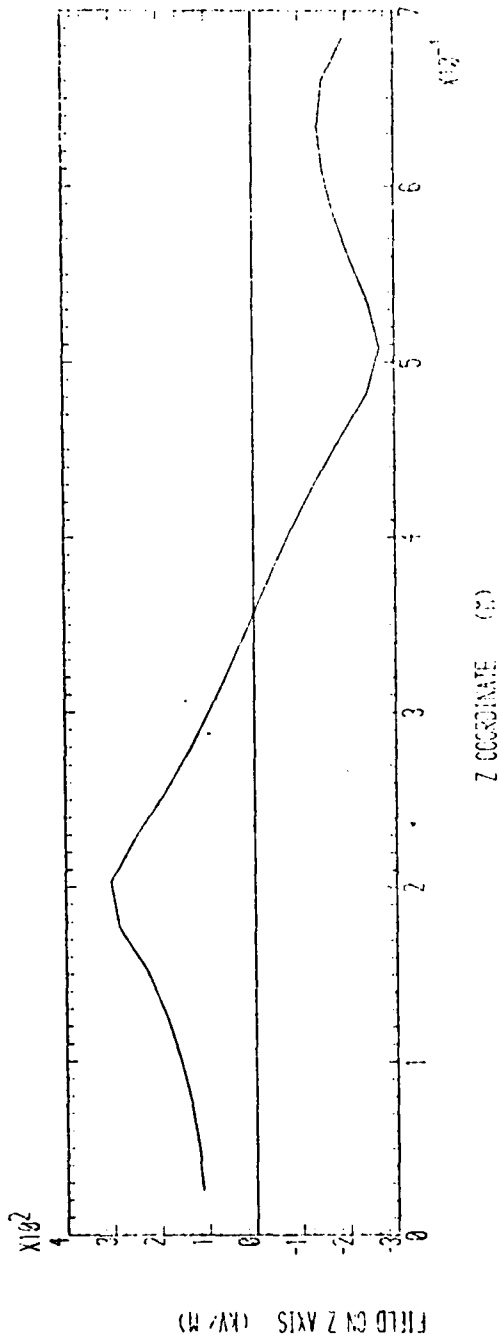
PLOT 13



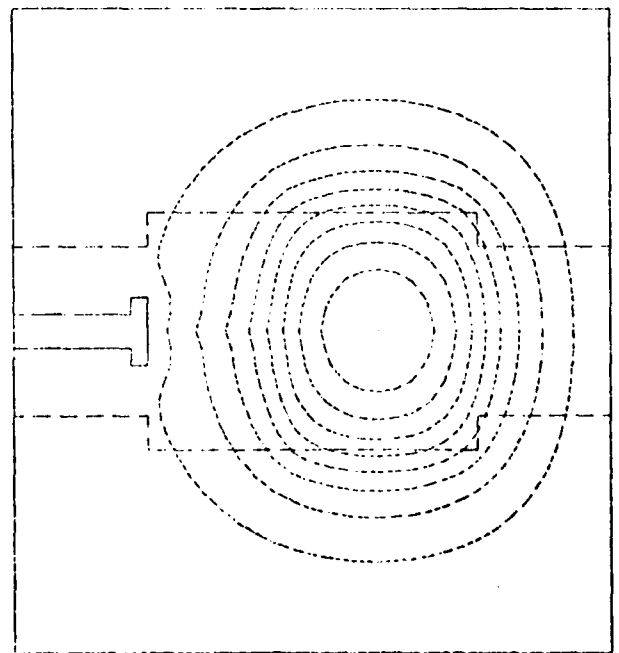
MINIMUM POTENTIAL	(KV) .0000E 0
MAXIMUM POTENTIAL	(KV) .4720E 5
CHARGE DENSITY IN FUEL	(C/M3) .1000E -3
CHARGE DISTRIBUTION ON FOAM	(C/M2) .0000E 0
FILLING LEVEL	(M) .0000E 0
CONTOUR SPACING	(KV) .5000E 4



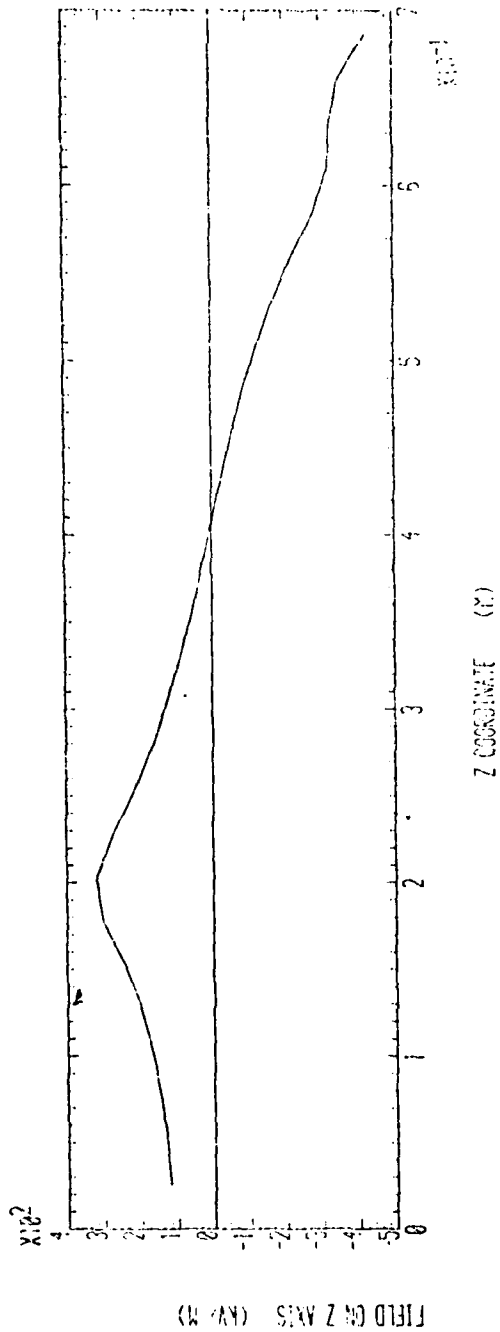
PLOT 14



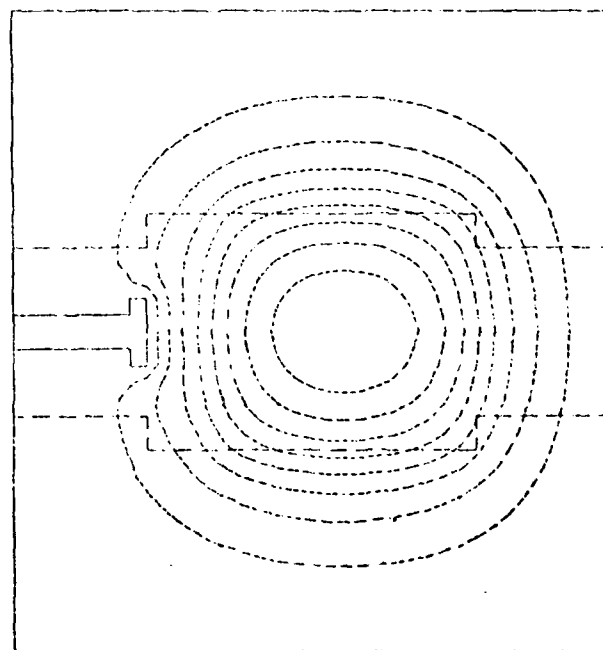
MINIMUM POTENTIAL	(KV) .0000E 0
MAXIMUM POTENTIAL	(KV) .0000E 0
CHARGE DENSITY IN FUEL	(C/M3) .0000E 0
CHARGE DISTRIBUTION ON FOAM	(C/M2) .0000E 0
FILLING LEVEL	(M) .0000E 0
CONTOUR SPACING	(KV) .0000E 0



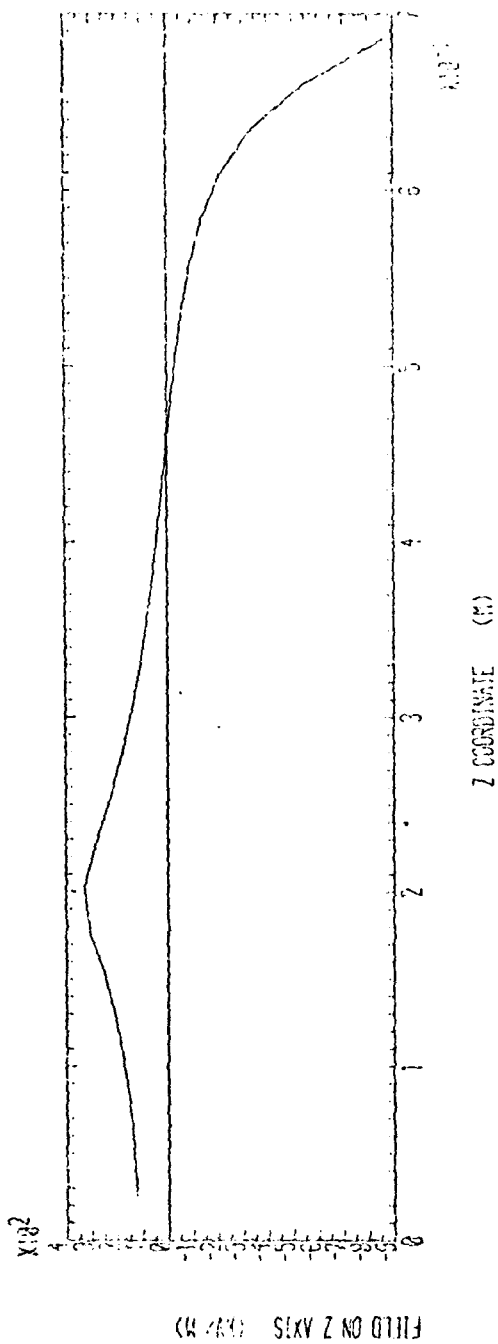
PLOT 15



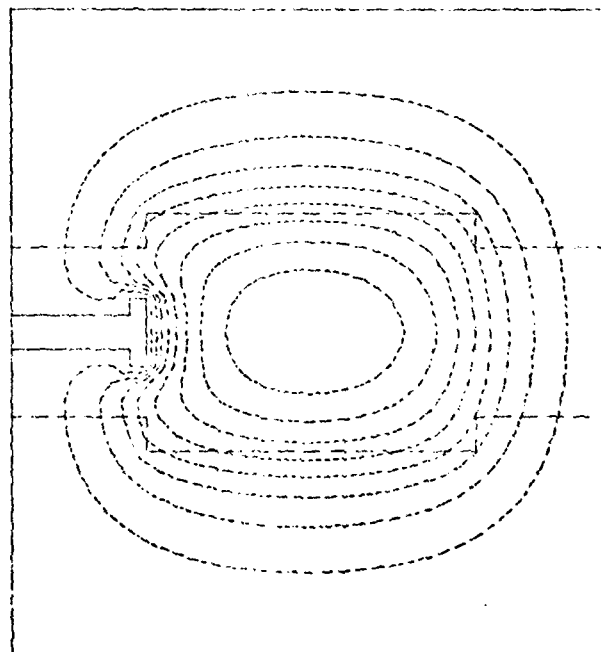
MINIMUM POTENTIAL LAV3 .0000E 0
 MAXIMUM POTENTIAL LAV3 .8770E 0
 CHARGE DENSITY IN FUEL IC7R3J .1000E 0
 CHARGE DISTRIBUTION ON FGM IC7R2E .1000E 0
 FILLING LEVEL F10E .0000E 0
 CONTOUR SPACING IC9V1 .2410E 0



PLOT 16



MINIMUM POTENTIAL (KV) 1.0000E -3
 MAXIMUM POTENTIAL (KV) 1.7257E -3
 CHARGE DENSITY IN FUEL (C/M3) 1.0000E -3
 CHARGE DISTRIBUTION ON FOAM (C/M3) 1.0000E -3
 FILLING LEVEL (M) 1.0000E -3
 CONTOUR SPACING (KV) 1.0000E -4



PLOT 17

PLOTS 18 - 30

The configuration for plots 18 - 30 consists of foam Section 4 together with foam Sections 1 and 2 inserted. (See Figure 7).

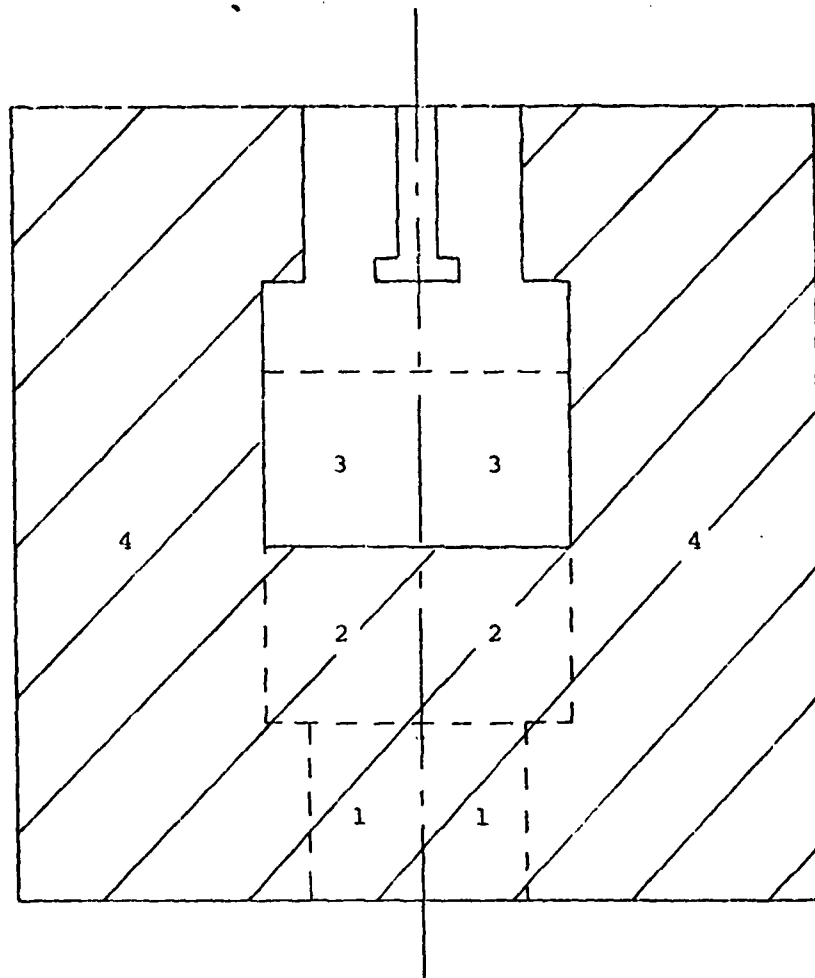
Plots 18 - 22 Charge density in fuel $= 10^{-4} \text{ C/m}^3$
 Charge density on foam surface $= 0 \text{ C/m}^2$
 Filling levels at .1, .2, .3, .4, .5 metres
 above base.

Plot 23 Surface charge density of 10^{-3} C/m^2 on Section 2
 upper surface only.

Plots 24 - 26 Surface charge on Section 2 upper surface and at
 heights .1, .2, .3 metres above this surface.

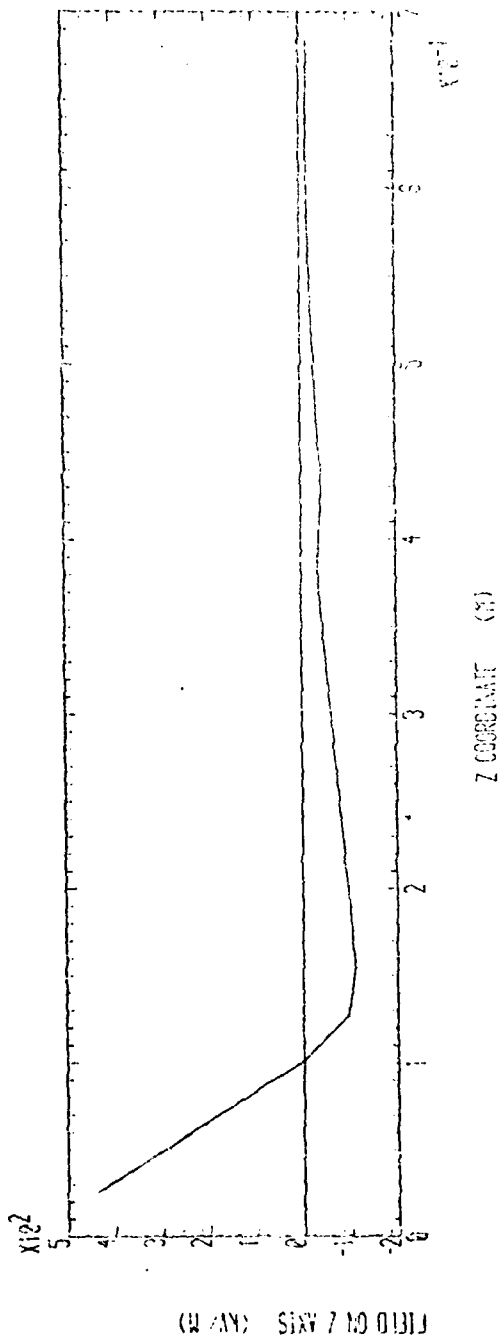
Plot 27 Vertical stream of fuel with charge density
 10^{-4} C/m^3 impinging on the target area.

Plots 28 - 30 Vertical stream of fuel + voiding region filled
 to heights .1, .2, .3 metres.

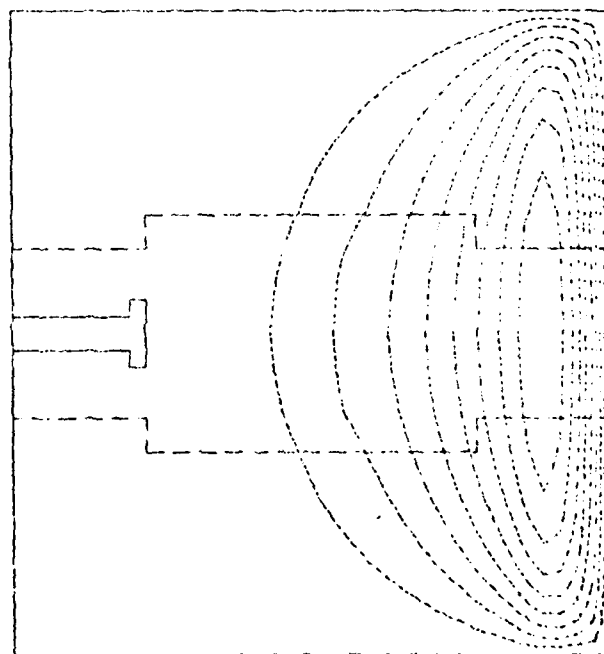


Foam sections 1 , 2 , and 4 in place

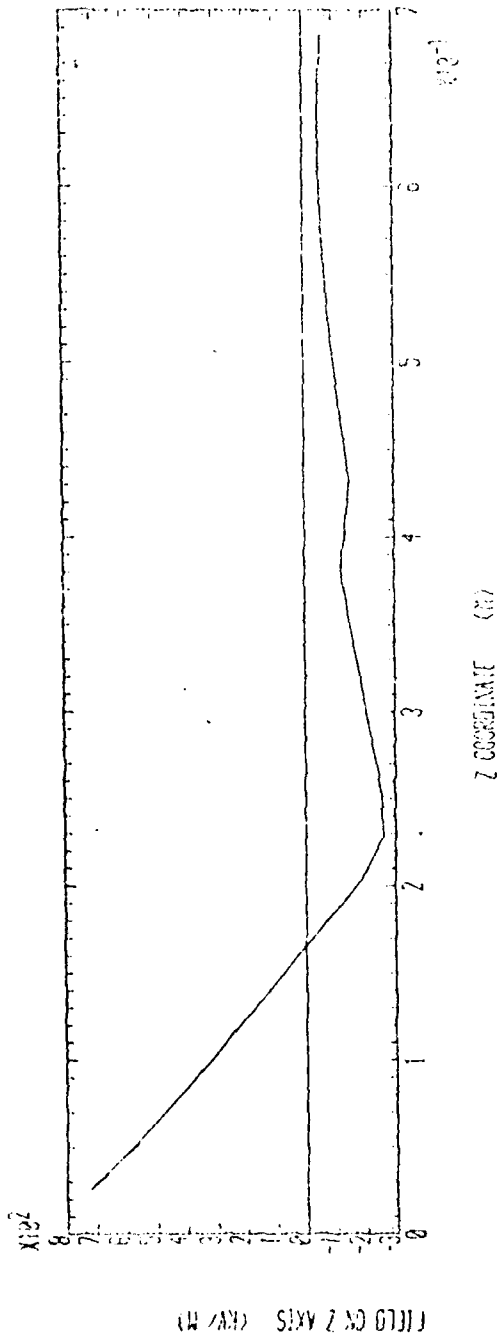
fig. 7.



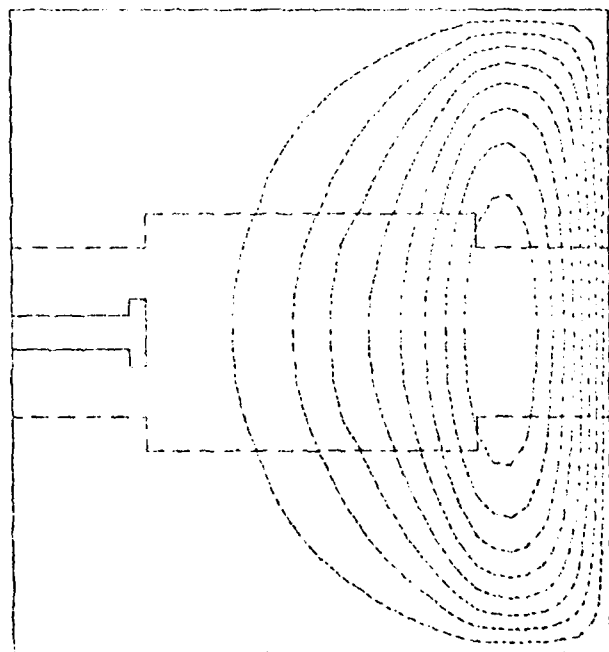
MINIMUM POTENTIAL (KV) ABOVE 0
 MAXIMUM POTENTIAL (KV) ABOVE 0
 CHARGE DENSITY IN FUEL (C/CM³) ABOVE -2
 CHARGE DISTRIBUTION ON FUEL (C/CM²) ABOVE 0
 FILLING LEVEL (CM) ABOVE 0
 CONTOUR SPACING (KV) ABOVE 0



PLOT 18



MINIMUM POTENTIAL AVG. DENSITY 2
 MAXIMUM POTENTIAL AVG. DENSITY 3
 CHARGE DENSITY IN FUEL DENSITY 4
 CHARGE DISTRIBUTION ON FUEL DENSITY 5
 FILLING LEVEL DENSITY 6
 CONTOUR SPACING DENSITY 7



PLOT 19

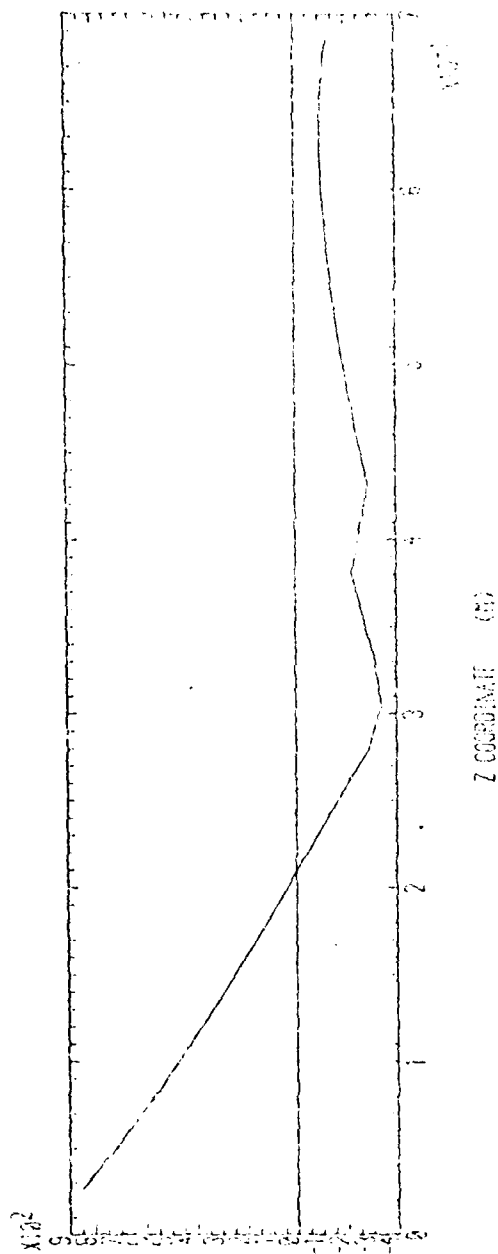
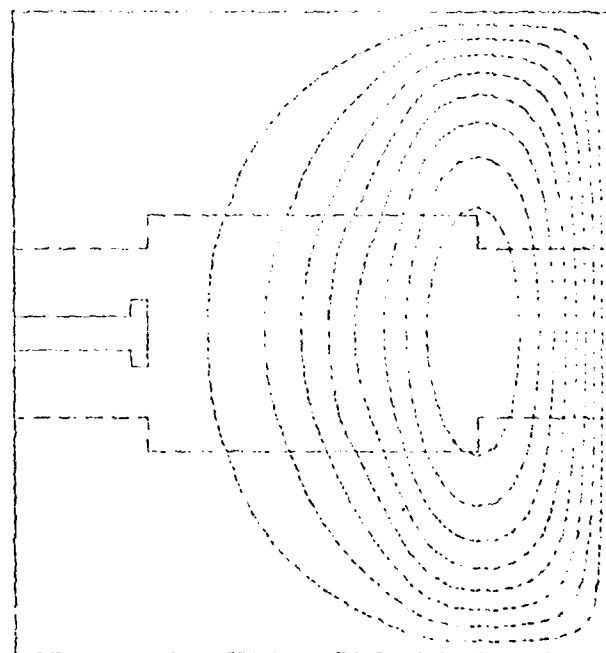
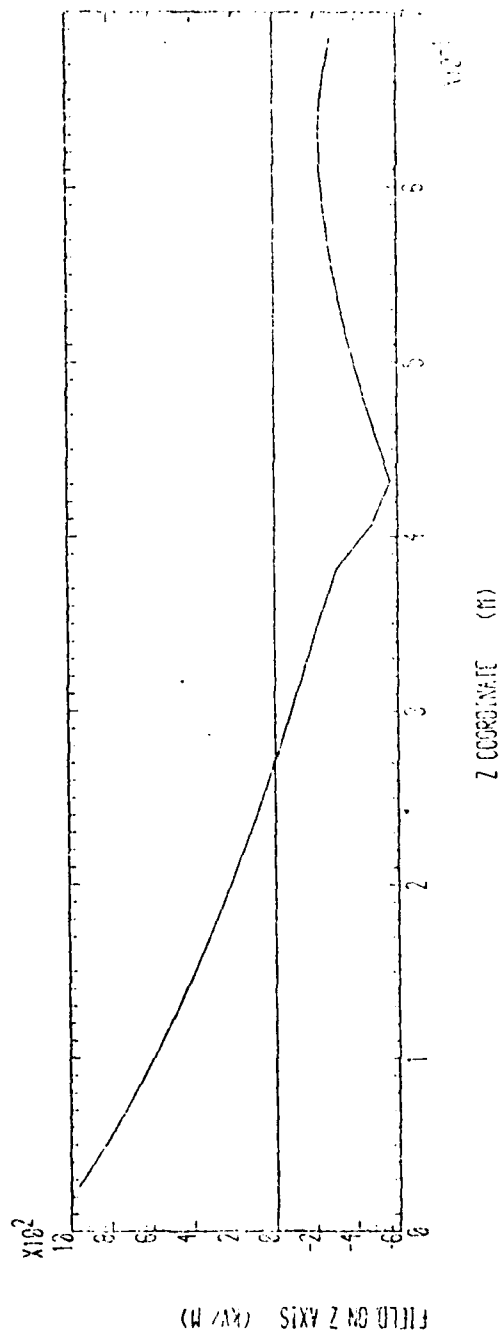


FIGURE 20 (a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m) (n) (o) (p) (q) (r) (s) (t) (u) (v) (w) (x) (y) (z)

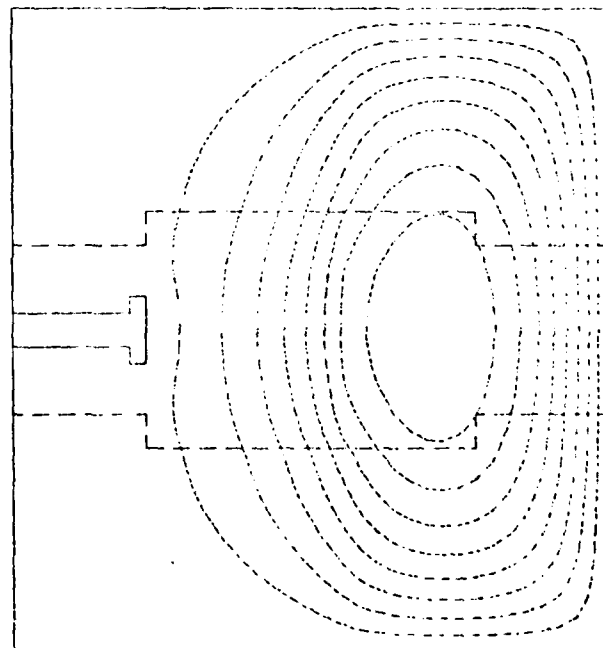
MINIMUM POTENTIAL
MAXIMUM POTENTIAL
CLASSE DENSITY IN FUEL
CHARGE DISTRIBUTION ON FOAM
FILLING LEVEL
CONTAINER CHARGING



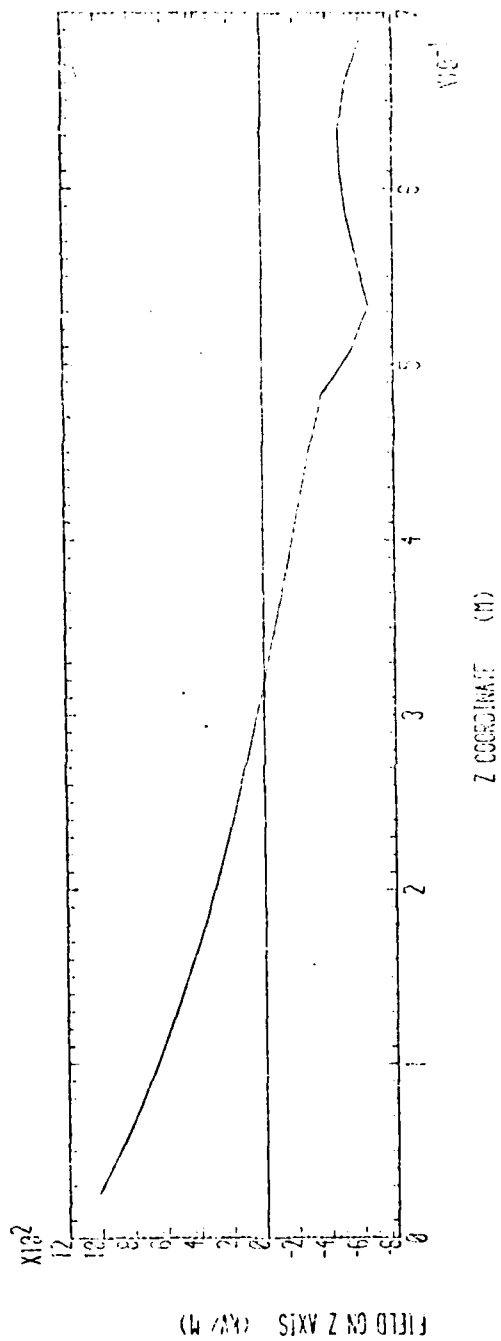
PLOT 20



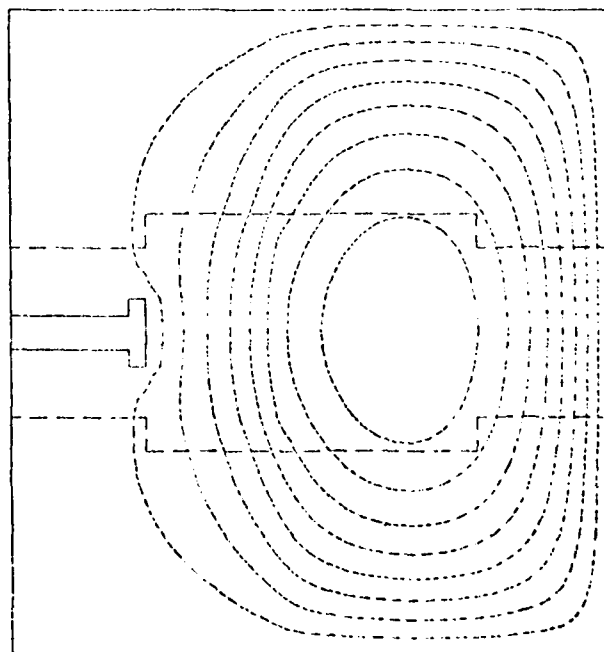
MINIMUM POTENTIAL XAVS 10.00E 0
 MAXIMUM POTENTIAL XAVS 1.000E 0
 CHARGE DENSITY IN FUEL 1.0000E -03
 CHARGE DISTRIBUTION ON FOAM 1.0000E -03
 FILLING LEVEL 1.0000E 0
 CONTOUR SPACING XAVS 1.00E 0



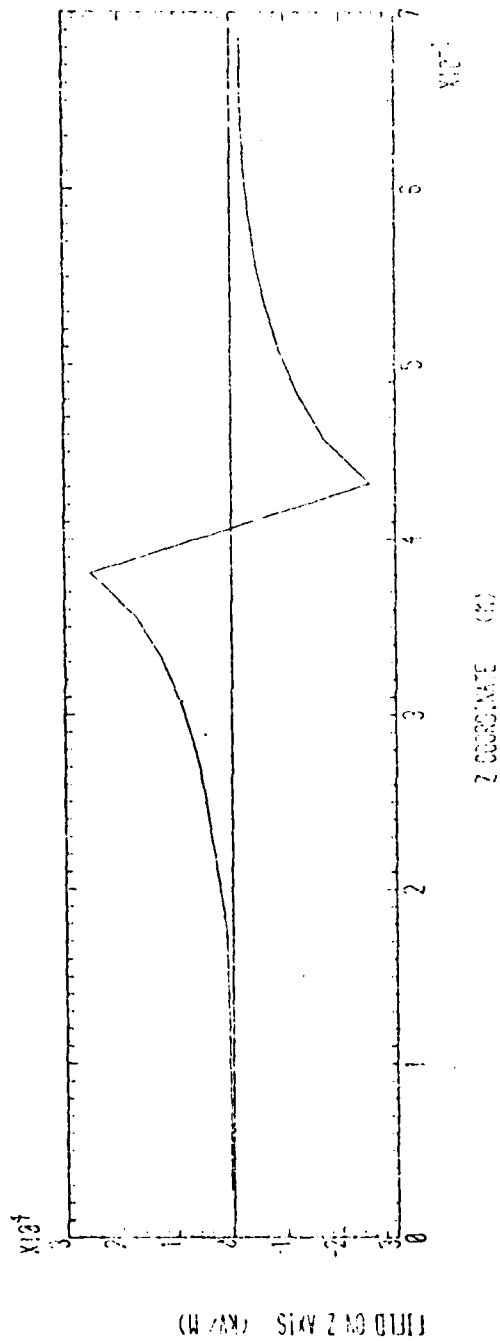
PLOT 21



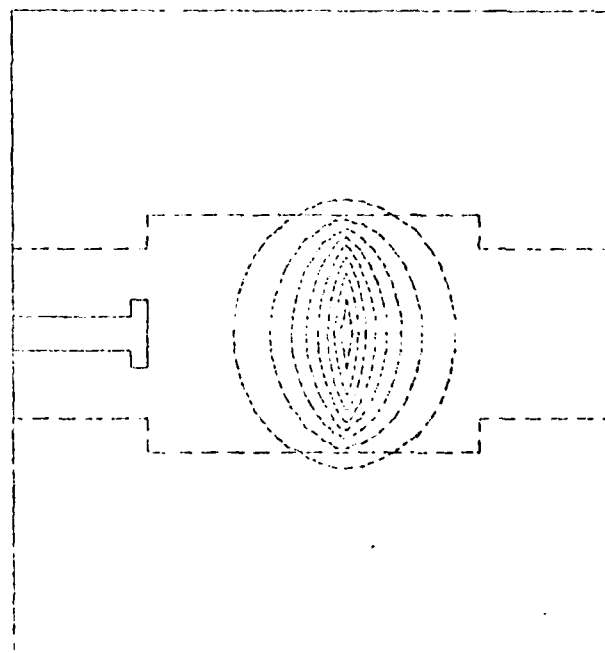
MINIMUM POTENTIAL (KV) 10000 0
 MAXIMUM POTENTIAL (KV) 10000 0
 CHARGE DENSITY IN FUEL (C/M³) 10000 0
 CHARGE DISTRIBUTION ON FUEL (C/M²) 10000 0
 FILLING LEVEL (M) 10000 0
 CONTOUR SPACING (M) 10000 0



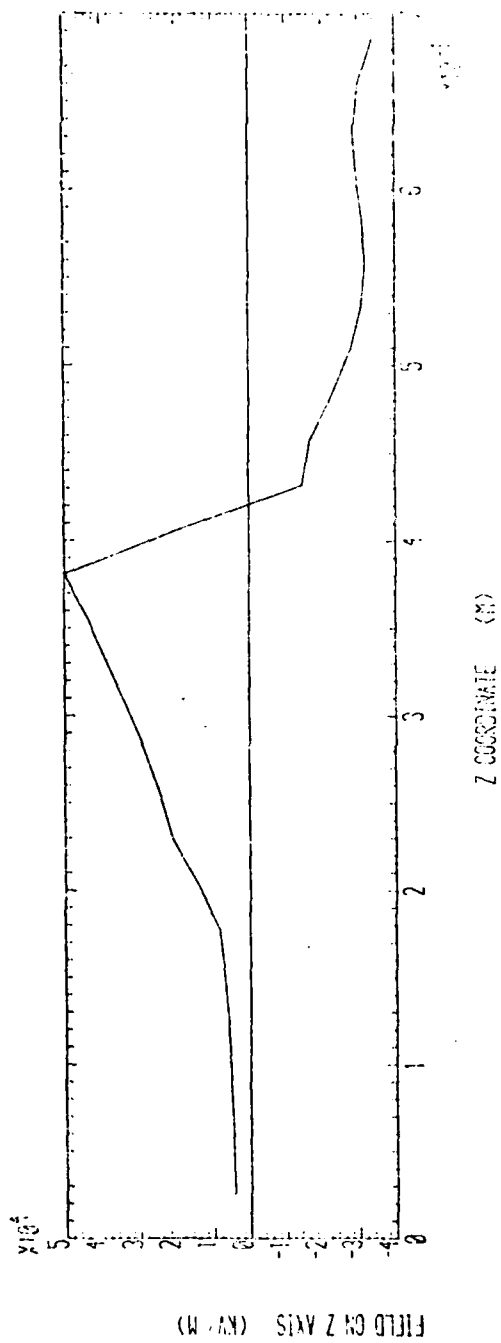
PLOT 22



MINIMUM POTENTIAL (KV) 0.000E 0
 MAXIMUM POTENTIAL (KV) 1.200E 0
 CHARGE DENSITY IN FUEL (C/M3) 1.000E 0
 CHARGE DISTRIBUTION ON FUEL (C/M3) 1.000E 0
 FILLING LEVEL (M) 0.000E 0
 CONTOUR SPACING (KV) 1.200E 0



PLOT 23



MINIMUM POTENTIAL (KV) .2000E 0

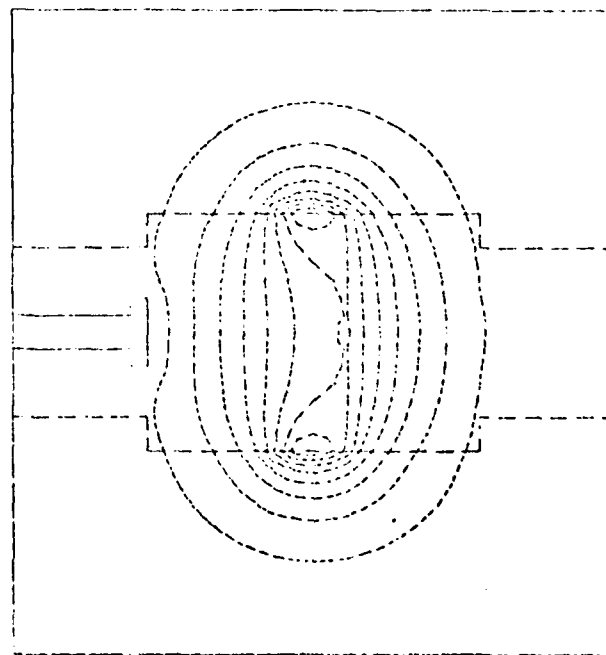
MAXIMUM POTENTIAL (KV) .1100E 0

CHARGE DENSITY IN FUEL (C/M3) .2000E 0

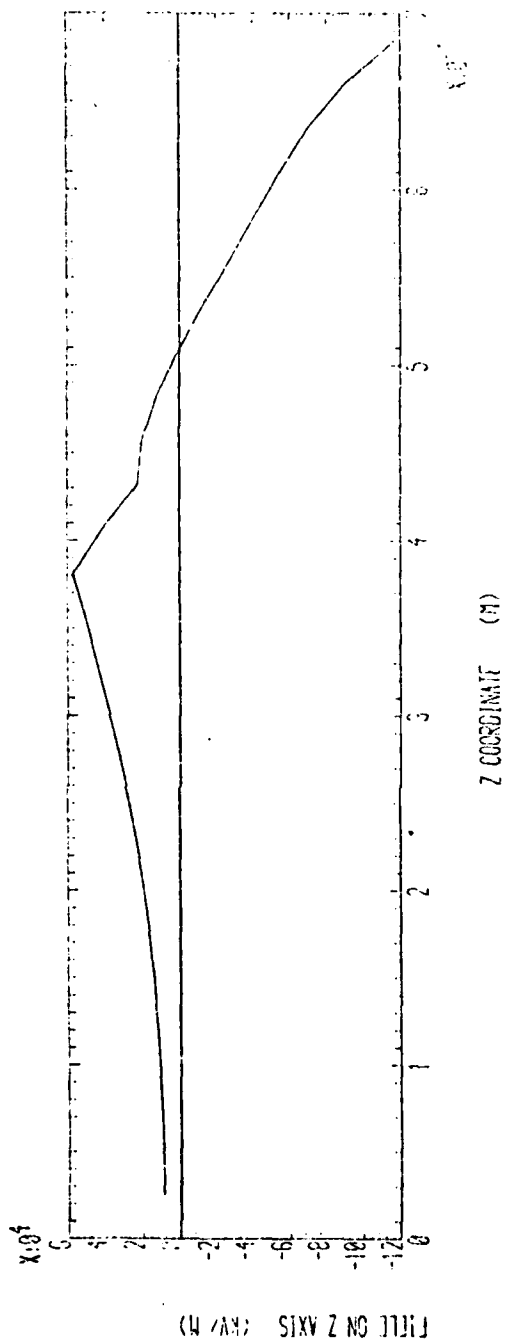
CHARGE DISTRIBUTION ON FOAM (C/M2) .1000E -2

FILLING LEVEL (MG) .3000E 0

CONTOUR SPACING (KV) .1100E 0

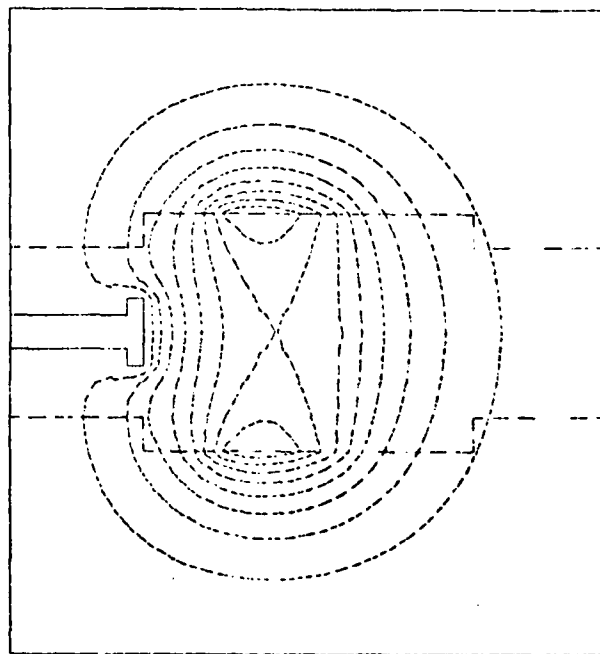


PLOT 24

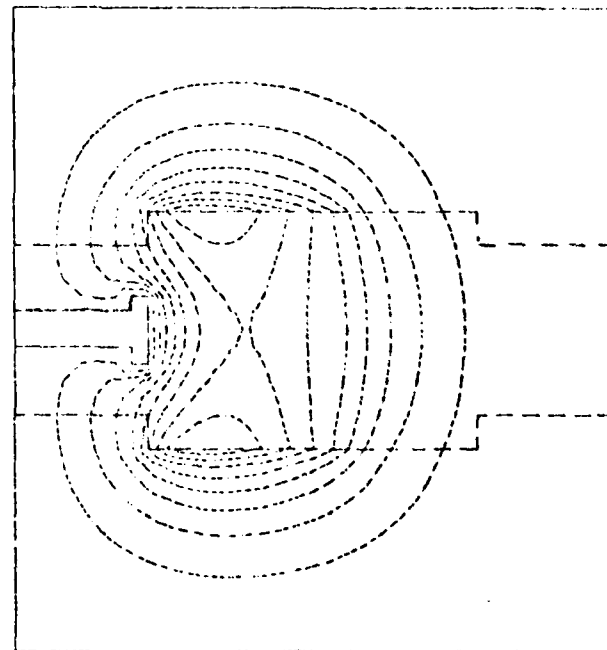
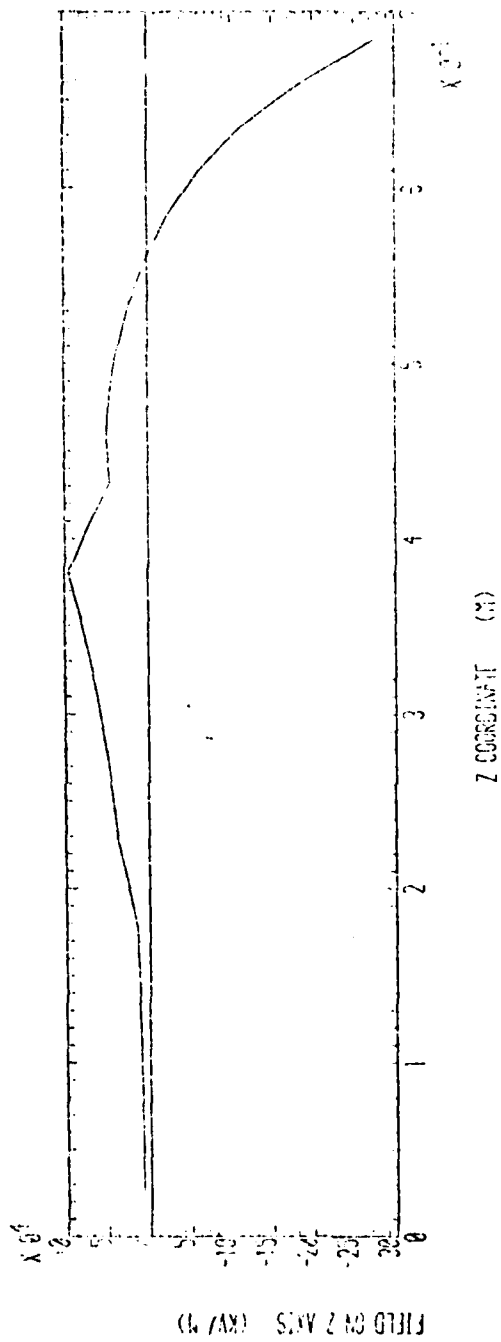


MINIMUM POTENTIAL
MAXIMUM POTENTIAL
CHARGE DENSITY IN FIELD
CHARGE DISTRIBUTION ON FOAM
FILLING LEVEL
CONTOUR SPACING

DATA SOURCE 0
DATA SOURCE 5
DATA SOURCE 0
DATA SOURCE 0
DATA SOURCE 0
DATA SOURCE 0



PLOT 25



MINIMUM POTENTIAL (KV) (LINE 0)

MAXIMUM POTENTIAL (KV) (LINE 0)

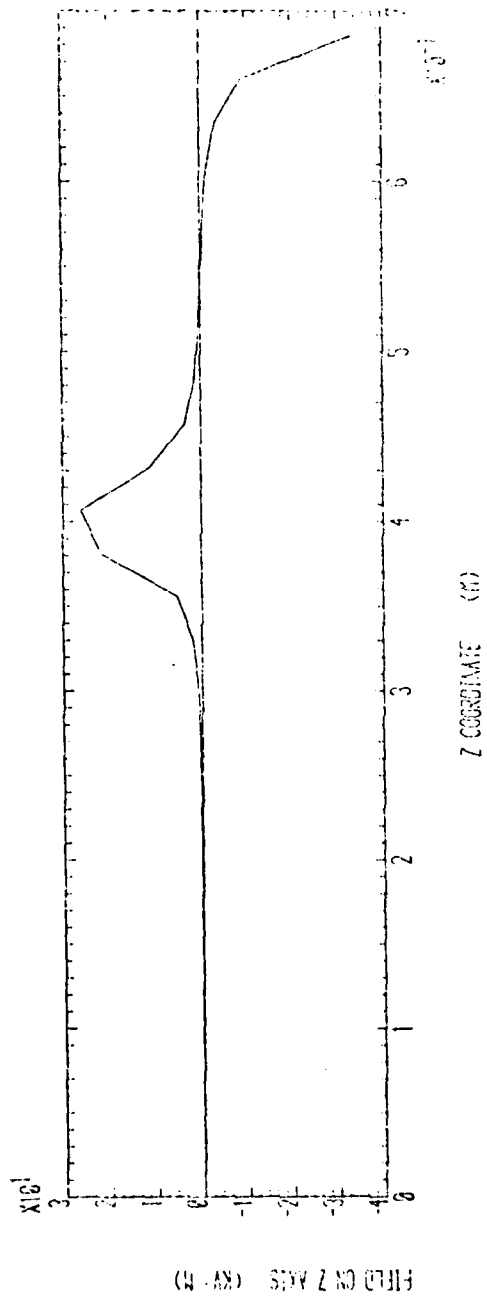
CHARGE DENSITY IN FUEL (C/M³) (LINE 0)

CHARGE DISTRIBUTION ON FOAM (C/M³) (LINE 0)

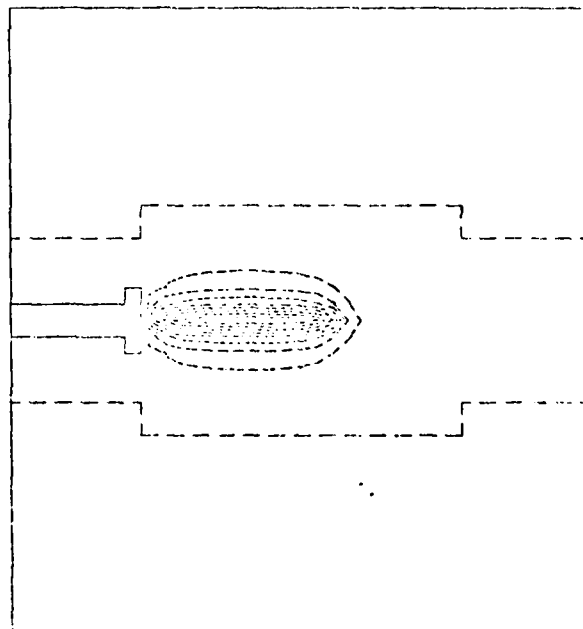
FILLING LEVEL (LINE 0)

CONTOUR SPACING (KV) (LINE 7)

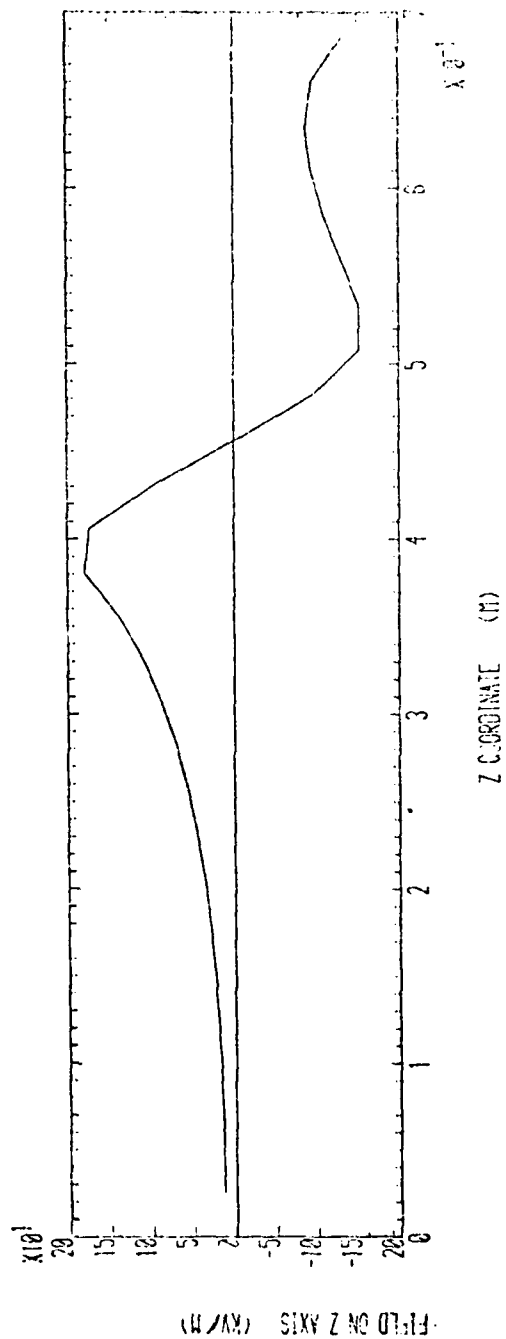
PLOT 26



MINIMUM POTENTIAL	(KV) .0000E 0
MAXIMUM POTENTIAL	(KV) .1800E 4
CHARGE DENSITY IN FUEL	(C/M3) .1000E -3
CHARGE DISTRIBUTION ON FOAM	(C/M2) .0000E 0
FILLING LEVEL	(M) .0000E 0
CONTOUR SPACING	(KV) .0010E 3



PLOT 27



MINIMUM POTENTIAL 0.000E 0

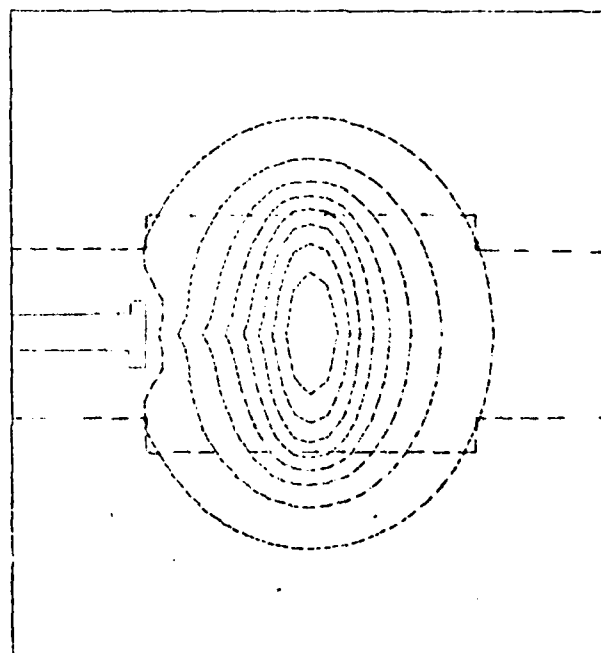
MAXIMUM POTENTIAL 0.000E 0

CHARGE DENSITY IN FUEL 0.000E 0

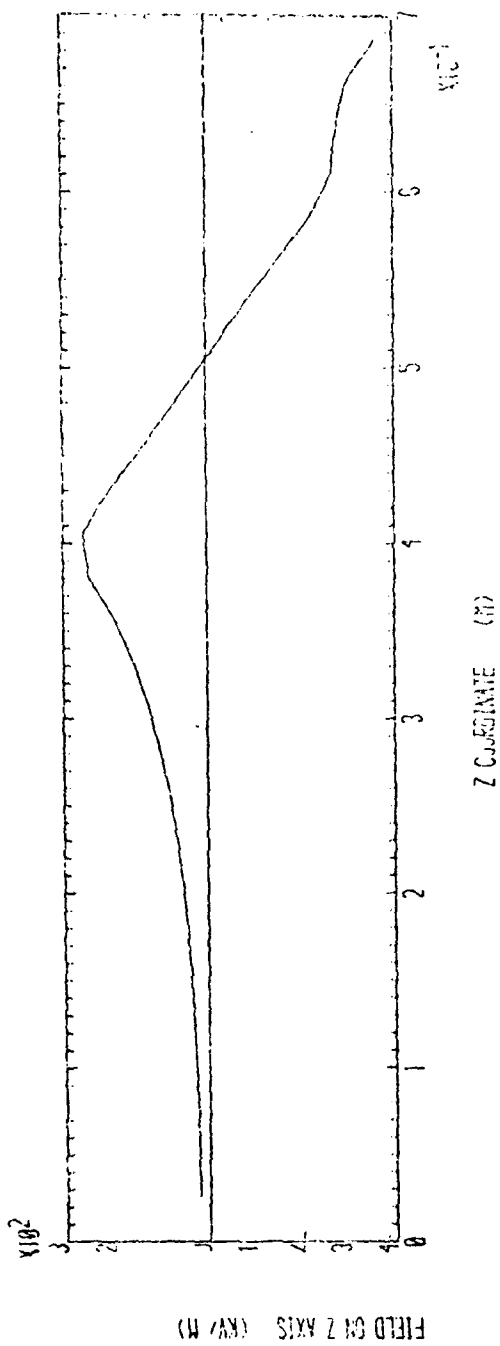
CHARGE DISTRIBUTION ON FOAM 0.000E 0

FILLING LEVEL 0.000E 0

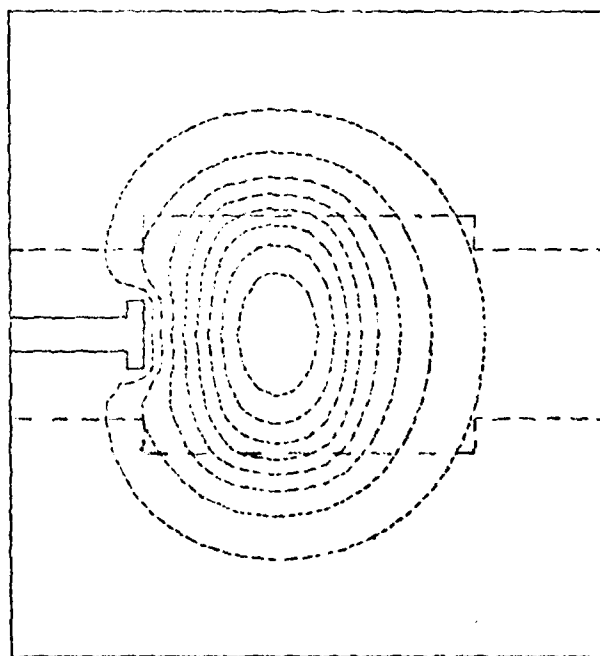
CONTOUR SPACING 0.000E 0



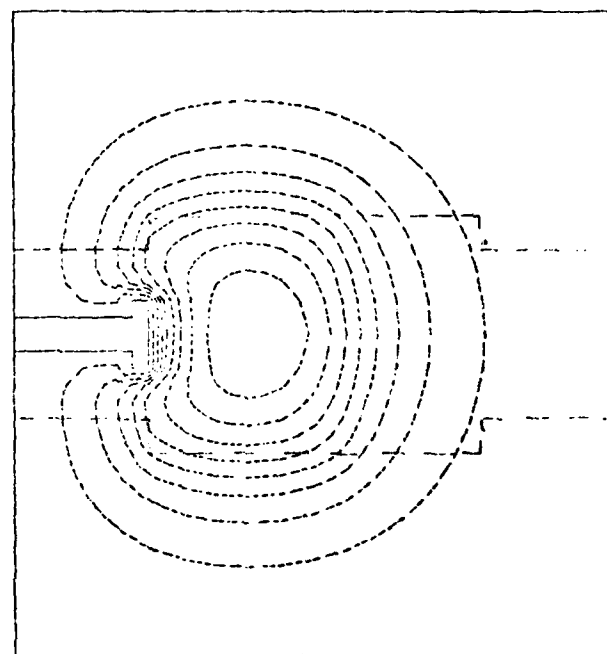
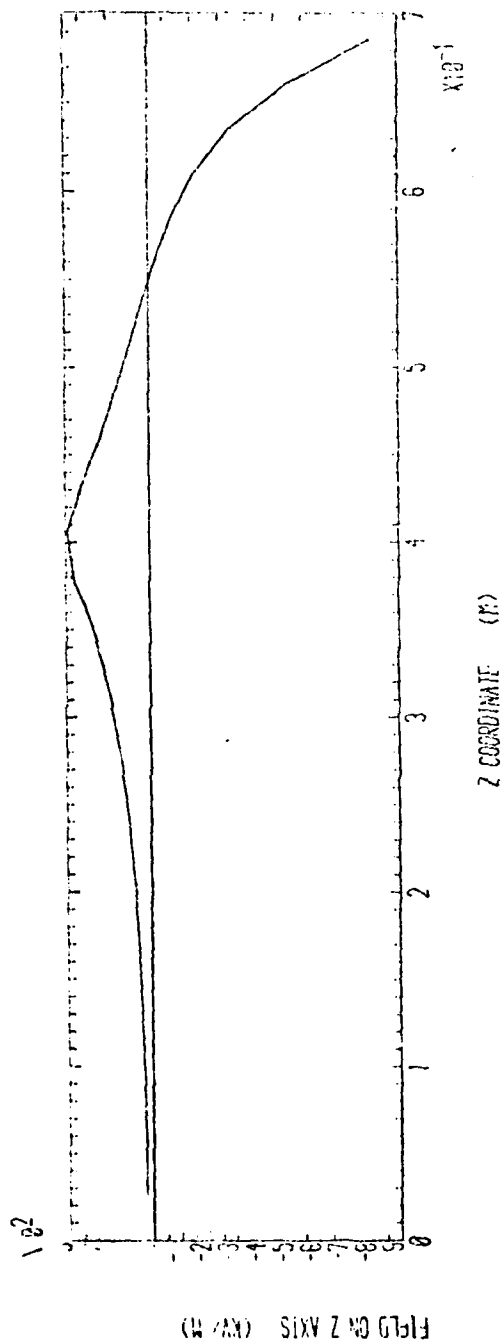
PLOT 28



MINIMUM POTENTIAL	1KV	.0000E 0
MAXIMUM POTENTIAL	1KV	.4743E 5
CHARGE DENSIT IN FUEL	CC/M3	.0000E -3
CHARGE DISTRIBUTION ON FOAM	CC/M3	.0000E 0
FILLING LEVEL	CM	.0000E 0
CONTOUR SPACING	1KV	.5271E 4



PLOT 29



MINIMUM POTENTIAL	(KV) .0000E 0
MAXIMUM POTENTIAL	(KV) .0000E 0
CHARGE DENSITY IN FEM	(C/M) .0000E -5
CHARGE DISTRIBUTION ON FOAM	(C/M) .0000E 0
FILLING LEVEL	(M) .0000E 0
CONTINUOUS SPACING	(KV) .0000E 0

PLOT 30

PLOTS 31 - 39

The configuration for plots 31-39 consists of foam Section 4 together with foam Sections 1, 2, and 3 inserted. (See Figure 8).

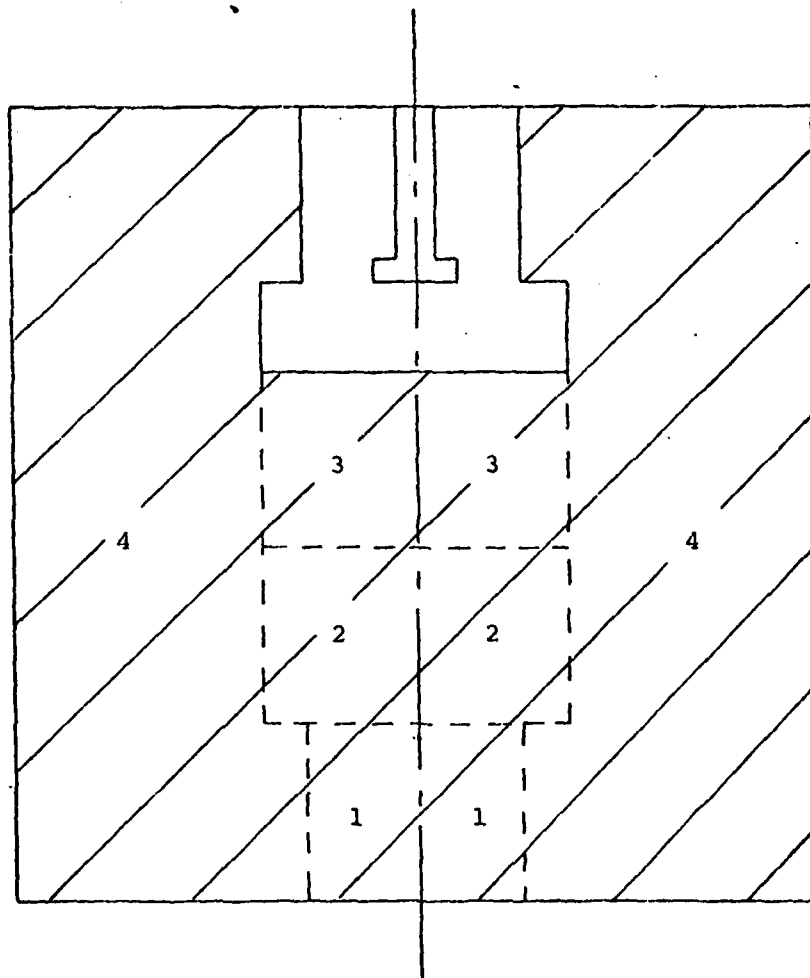
Plots 31 - 35 Charge density in fuel = 10^{-4} C/m³
 Charge density on foam surface = 0 C/m²
 Filling levels at .1, .2, .3, .4, .5 metres above base.

Plot 36 Surface charge density of 10^{-3} C/m² on Section 3
 upper surface only.

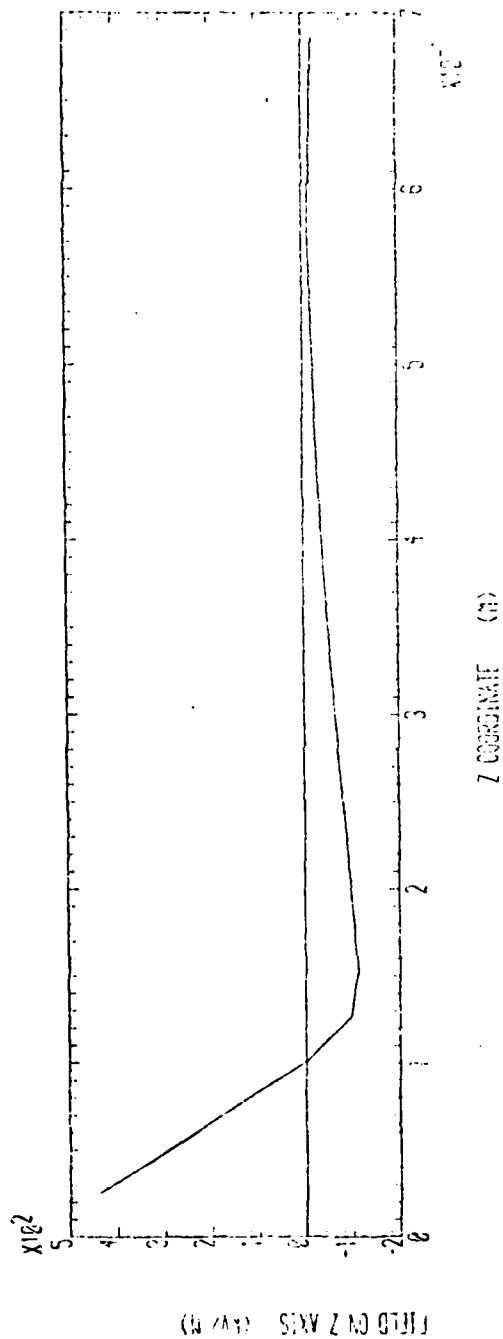
Plot 37 Surface charge on Section 3 upper surface and at
 height .1 metre above this surface.

Plot 38 Vertical stream of fuel with charge density 10^{-4} C/m³
 impinging on the target area.

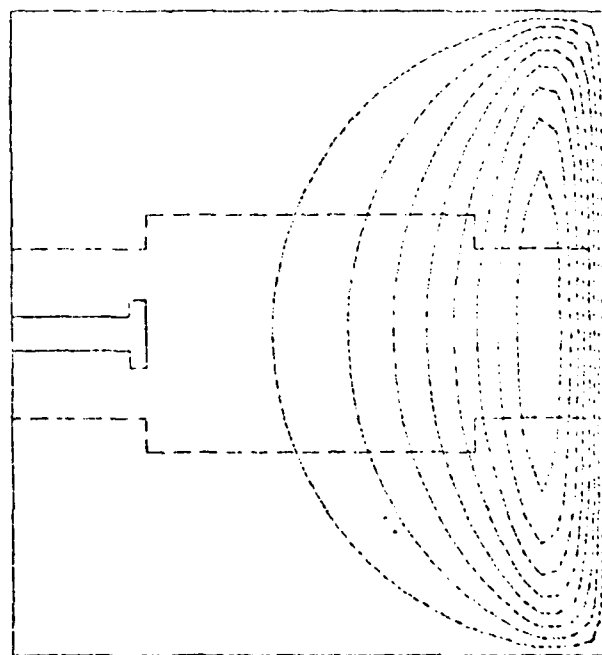
Plot 39 Voiding region filled with fuel.



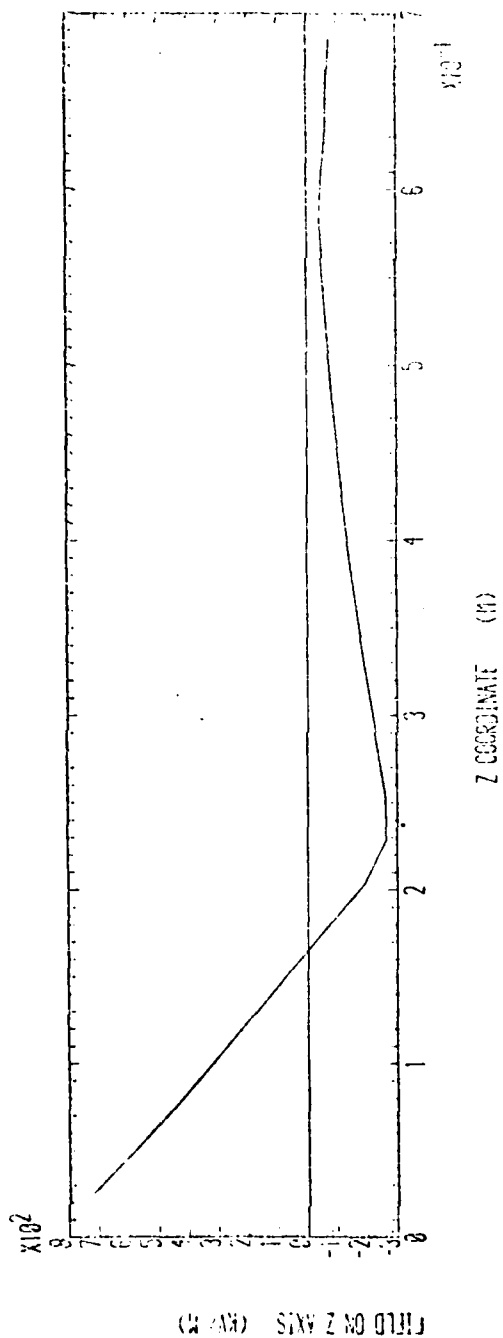
Foam sections 1 , 2 , 3 , and 4 in place fig. 8.



MINIMUM POTENTIAL	AVG. LOGS 4
MAXIMUM POTENTIAL	AVG. LOGS 5
CHARGE DENSITY IN FUEL	LOGS 1000E-08
CHARGE DISTRIBUTION ON FUEL	LOGS 1000E-08
FILLING LEVEL	LOG 1000E-08
CONTOUR SPACING	LOG 1000E-08



PLOT 31



MINIMUM POTENTIAL (AV) .00000 0

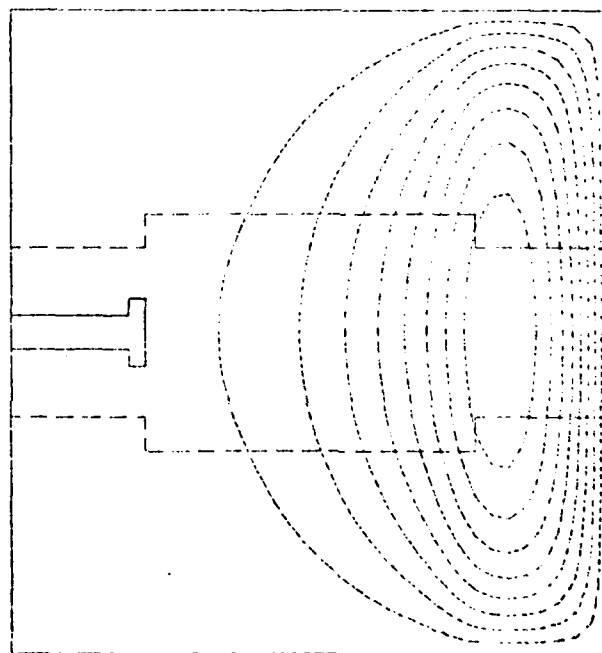
MAXIMUM POTENTIAL (AV) .00000 0

CHARGE DENSITY IN FUEL (C/M³) .00000 0

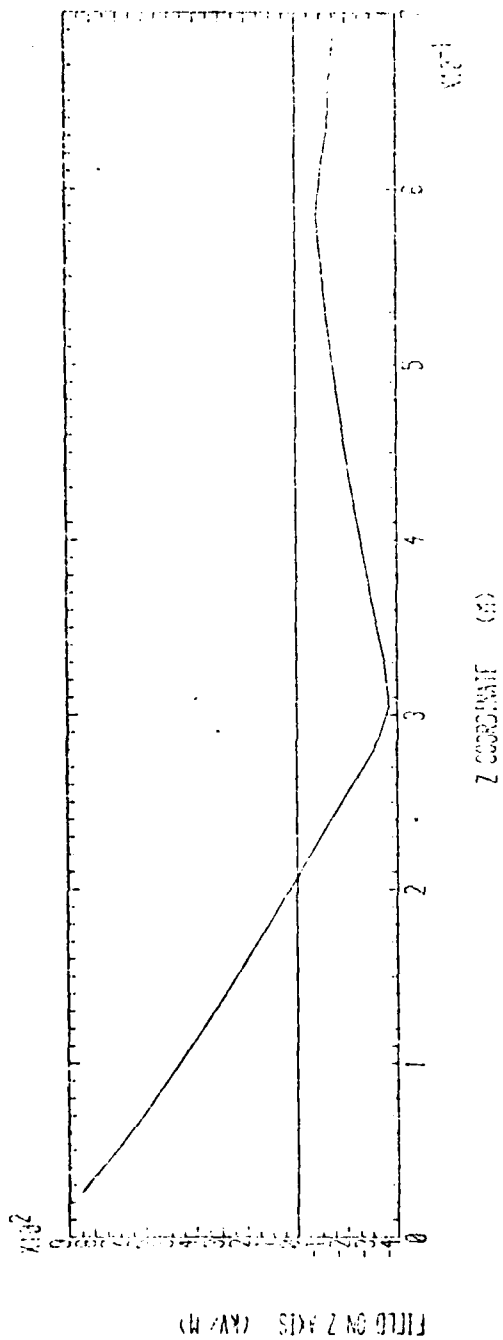
CHARGE DISTRIBUTION ON FURN (C/M²) .00000 0

FILLING LEVEL (M) .00000 0

CONTOUR SPACING (AV) .00000 0



PLOT 32



MINIMUM POTENTIAL (V) SCALE 0

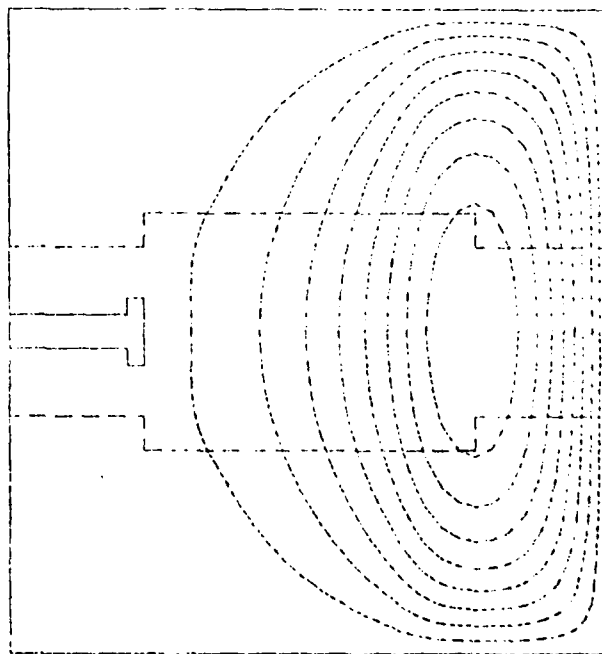
MAXIMUM POTENTIAL (V) SCALE 5

CHARGE DENSITY IN FUEL (C/M³) SCALE 0

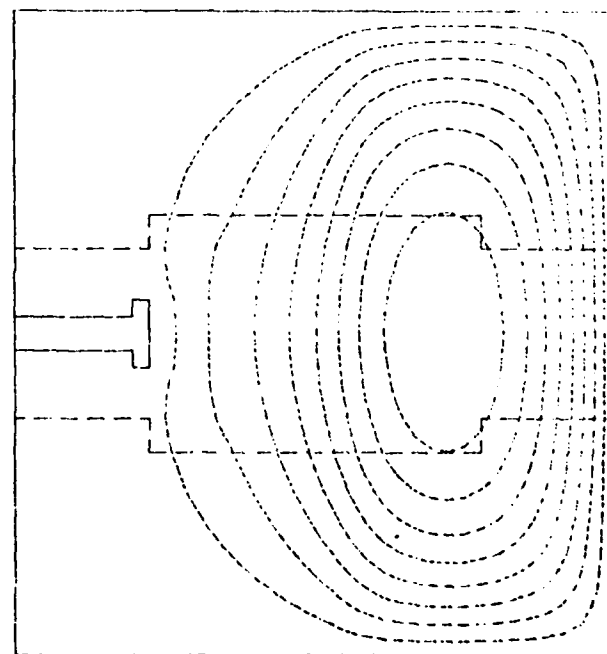
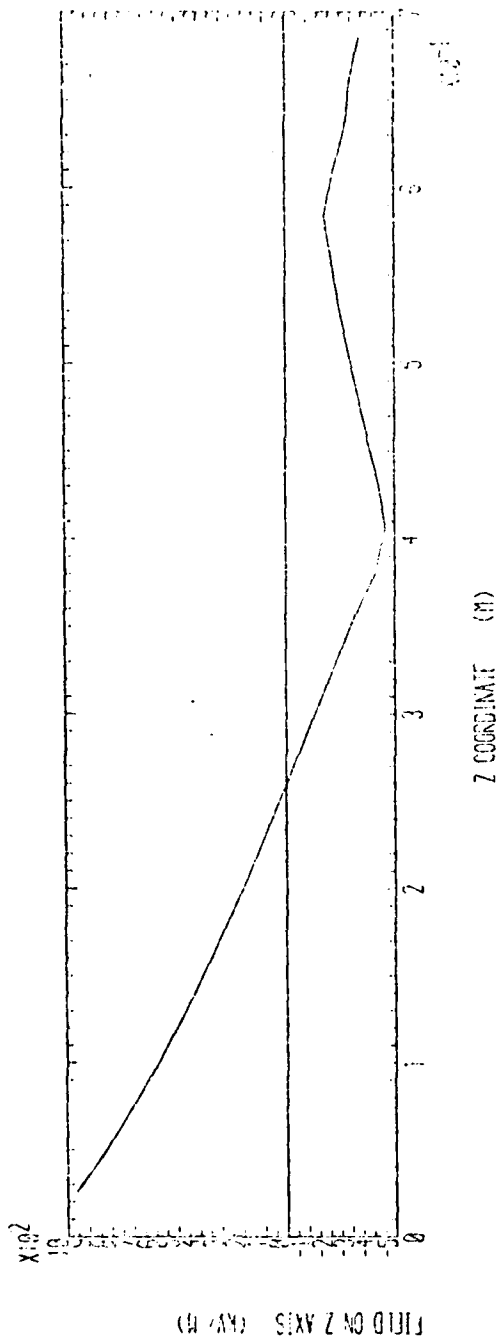
CHARGE DISTRIBUTION ON FUEL (C/M²) SCALE 0

FILLING LEVEL (M) SCALE 0

CONTAINER SPACING (M) SCALE 5

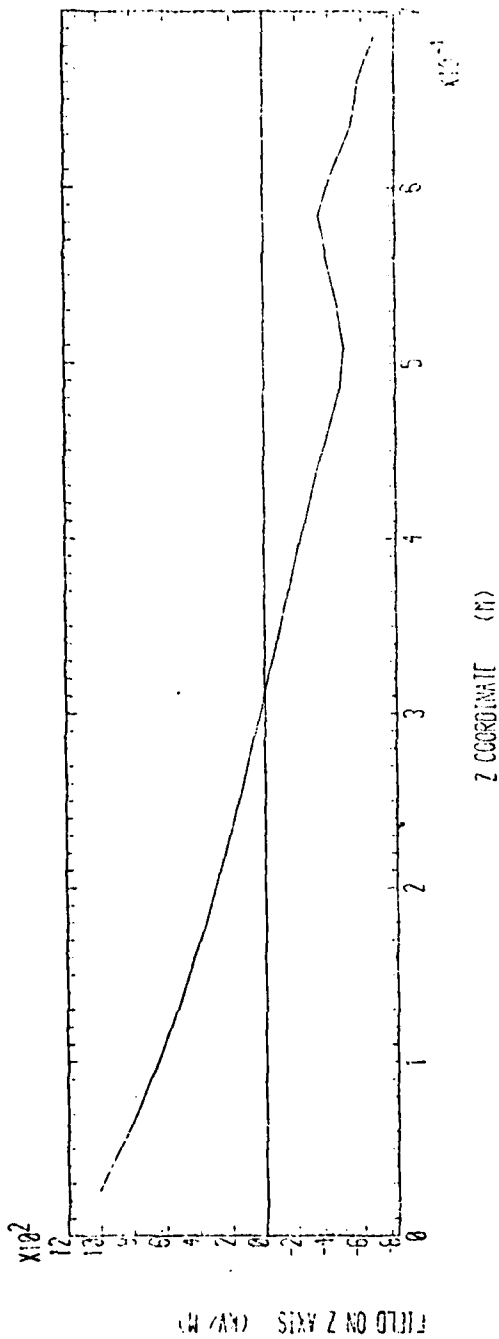


PLOT 33

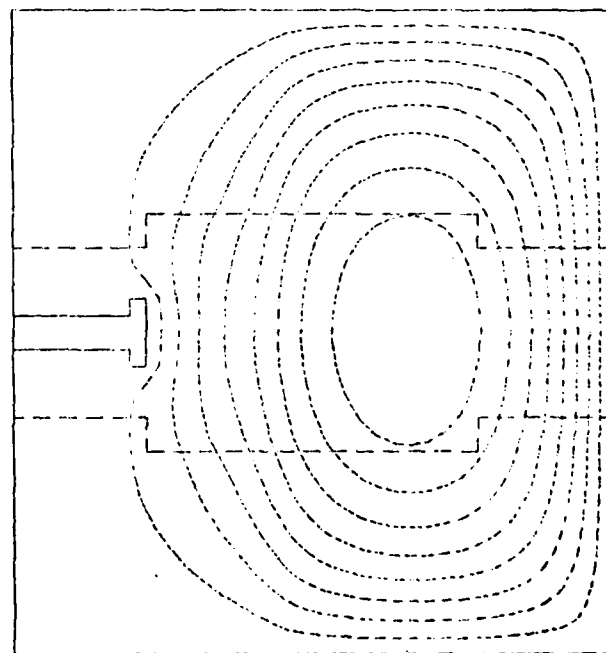


MINIMUM POTENTIAL	AV. M. 0.0000
MAXIMUM POTENTIAL	AV. M. 0.0000
CHARGE DENSITY IN FUEL	0.0000
CHARGE DISTRIBUTION ON FOAM	0.0000
FILLING LEVEL	0.0000
CONTOUR SPACING	0.0000

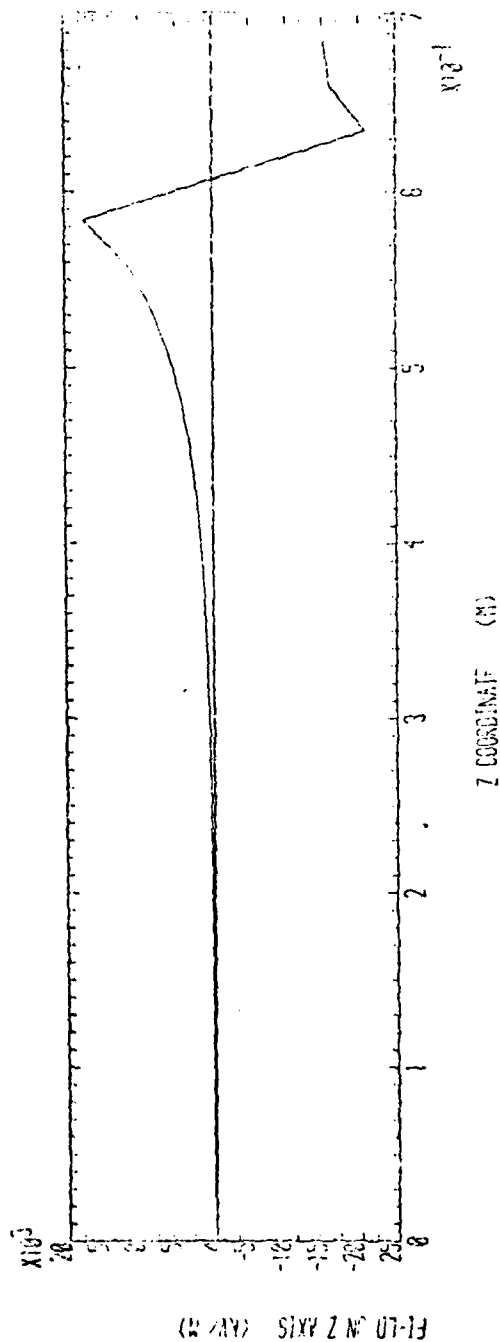
PLOT 34



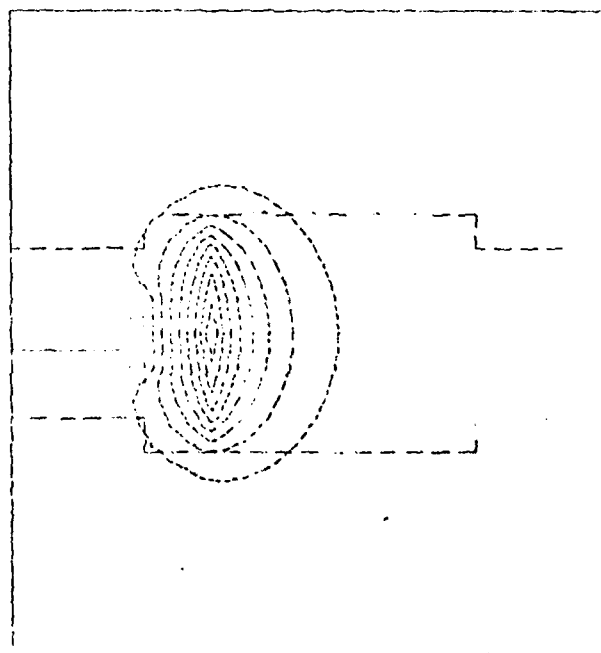
MINIMUM POTENTIAL	(KV) 1000 E 2
MAXIMUM POTENTIAL	(KV) 1000 E 6
CHARGE DENSITY IN FUEL	(C/CM ³) 1000 E 3
CHARGE DISTRIBUTION ON FUEL	(C/CM ²) 1000 E 2
FILLING LEVEL	(%) 1000 E 2
CONTOUR SPACING	(KV) 1000 E 5



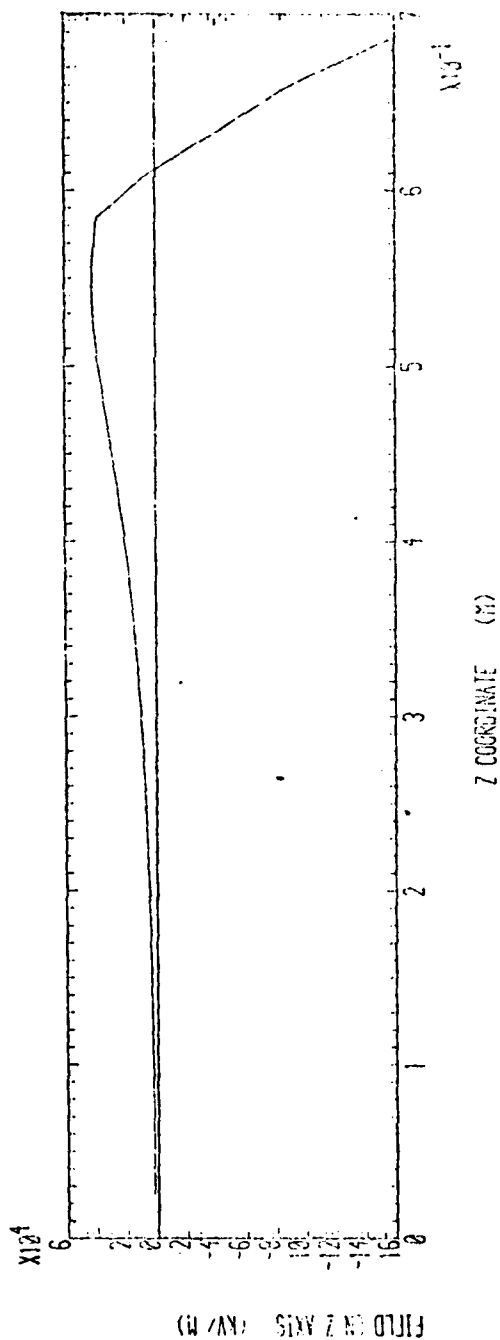
PLOT 35



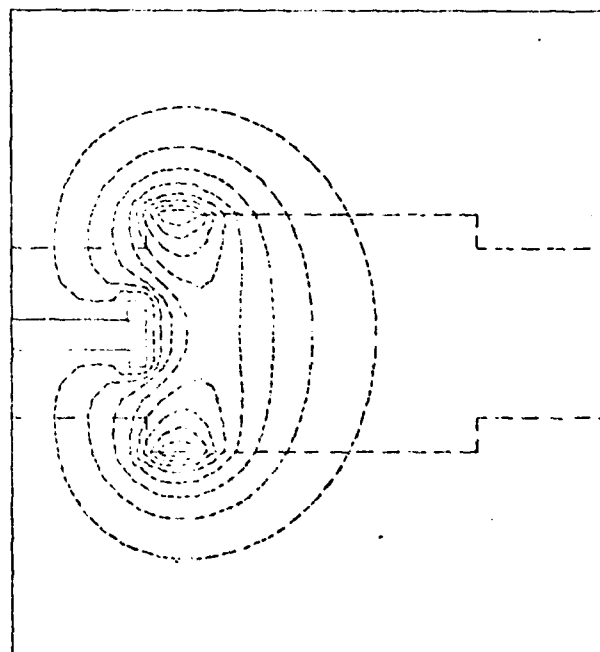
MINIMUM POTENTIAL IN 3 .00000 0
 MAXIMUM POTENTIAL IN 3 .00000 7
 CHARGE DENSITY IN FUEL IN 3 .00000 0
 CHARGE DISTRIBUTION ON FCM IN 3 .00000 0
 FILLING LEVEL IN 3 .00000 0
 CONTOUR SPACING IN 3 .00000 0



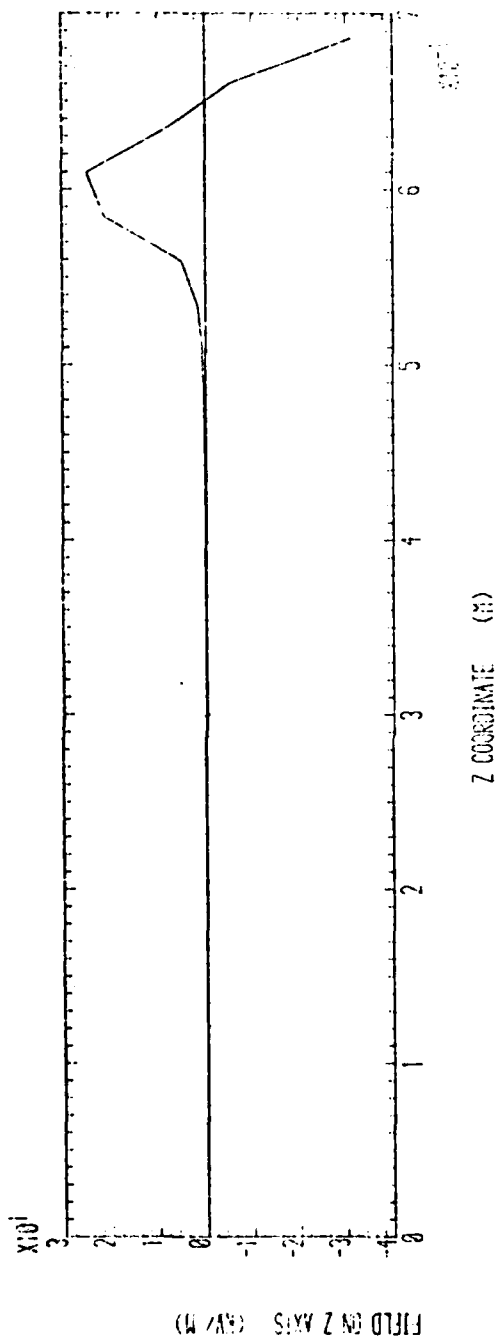
PLOT 36



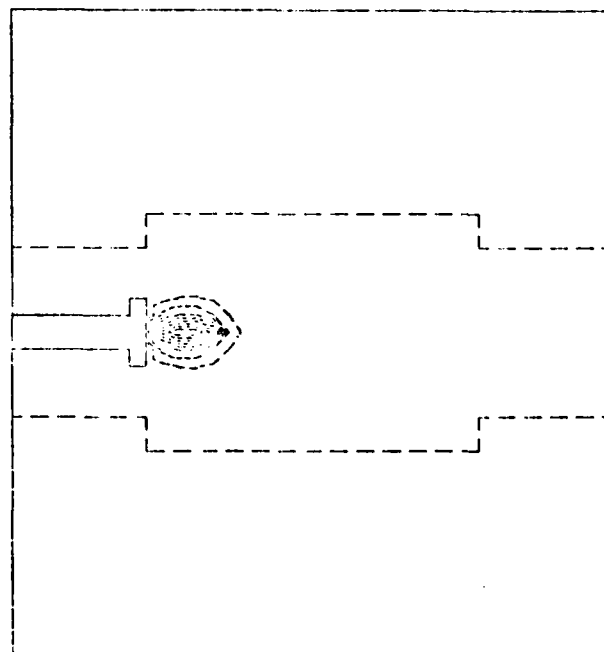
MINIMUM POTENTIAL	(KV) .0000E 0
MAXIMUM POTENTIAL	(KV) .1500E 0
CHARGE DEN IT IN FUEL	(C/M3) .0000E 0
CHARGE DISTRIBUTION ON FOAM	(C/M2) .1000E -2
FILLING LEVEL	(M) .0000E 0
CONTOUR SPACING	(KV) .2155E 7



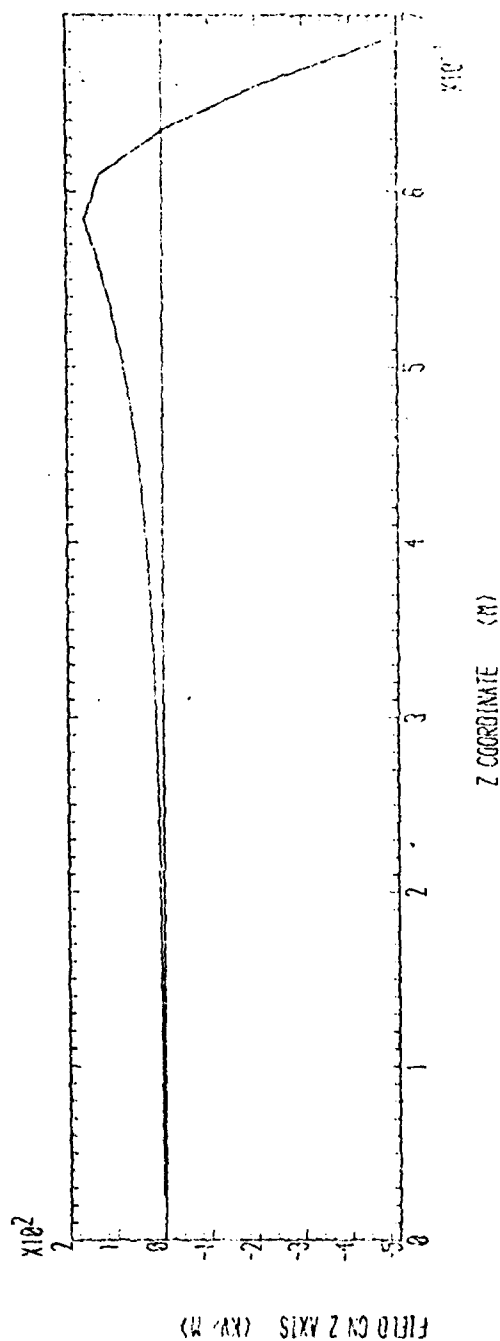
PLOT 37



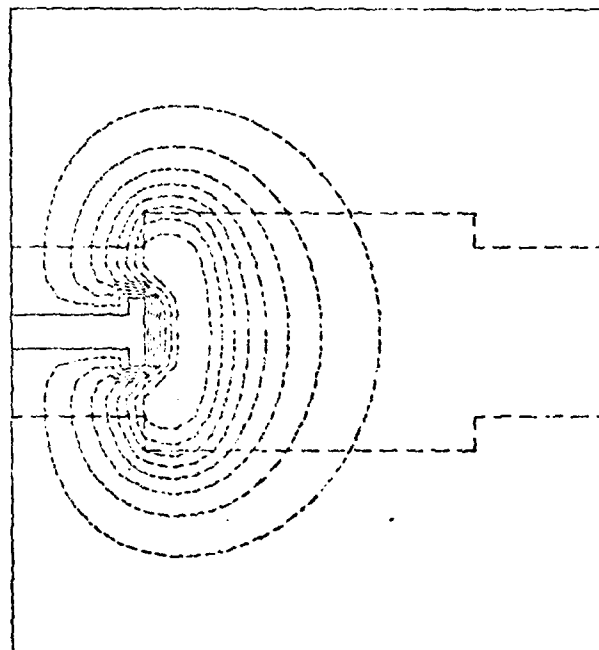
MINIMUM POTENTIAL	(AV) .0000E 0
MAXIMUM POTENTIAL	(AV) .1550E 4
CHARGE DENSITY IN FUEL	(C/CM3) .1000E -3
CHARGE DISTRIBUTION ON FOAM	(C/CM2) .0000E 0
FILLING LEVEL	(M) .0000E 0
CONTOUR SPACING	(KV) .1750E 3



PLOT 38



MINIMUM POTENTIAL	(KV)	.8300E 0
MAXIMUM POTENTIAL	(KV)	.2689E 5
CHARGE DENSITY IN FUEL	(C/M3)	.1000E -3
CHARGE DISTRIBUTION ON FOAM	(C/M2)	.0000E 0
FILLING LEVEL	(M)	.0000E 0
CONTOUR SPACING	(KV)	.2687E 4

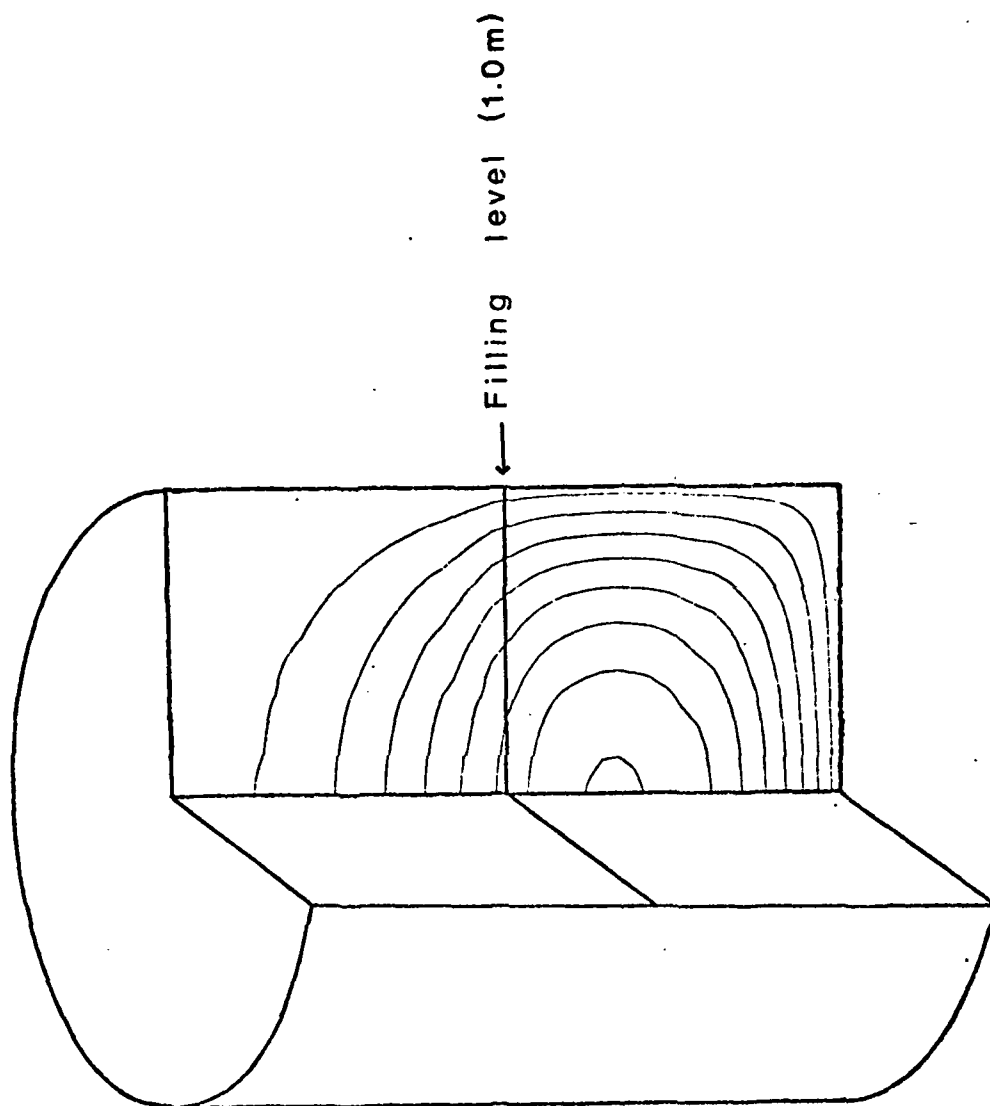


PLOT 39

APPENDIX A

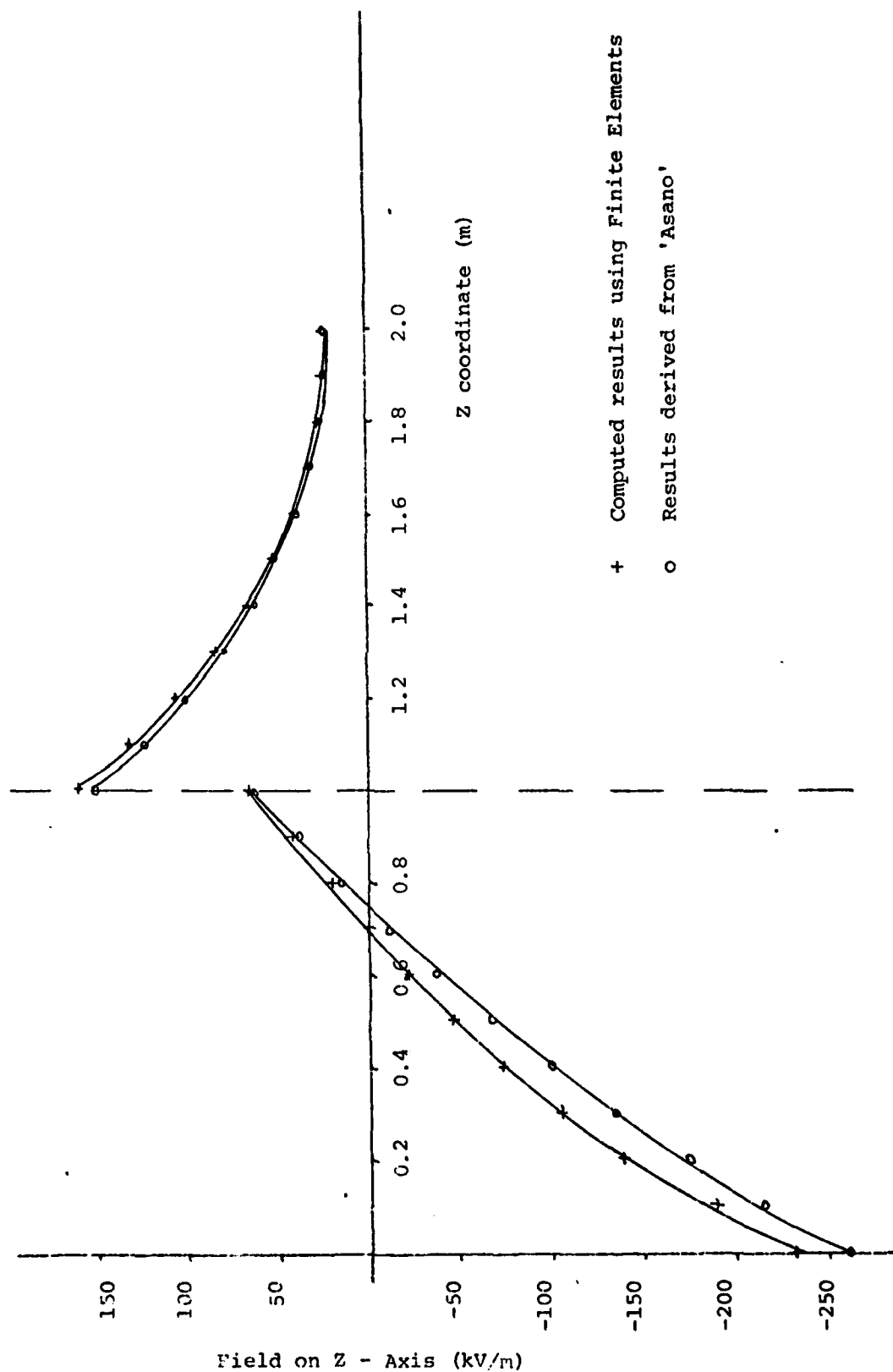
PROGRAM VALIDATION

The finite element program used in this study was written in FORTRAN. To test the accuracy of the program, it was checked against a problem for which an analytical solution has been found. Asano (Ref. 6) has provided an analytical solution for the potential in a cylindrical earthed metal tank half filled with charged liquid, assuming a uniform charge density. This problem was solved using the finite element program with a mesh of 760 nodes, and an equipotential map was drawn (Figure A1). The parameter chosen for comparison was the field along the cylinder axis. As can be seen from Figure A2, the finite element program produced results in good agreement with those of Asano.



Metal tank
Radius - 1.0 m
Height - 2.0 m

Fig. A1



Validation using 'Asano' results

Fig. A2

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